Systems Analysis of Urban Air Mobility Operational Scaling

by

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Abstract

Urban air mobility (UAM) refers to a set of vehicles and operational concepts that provide on-demand or scheduled air transportation services for passengers and cargo within a metropolitan area. Prior UAM systems based on helicopters or small aircraft did not achieve sustained, large-scale adoption. The goals of this thesis are: to identify the principal scaling constraints of UAM, to discern how the severity of these constraints varies with different implementation locations and operational concepts, and to assess the feasibility of large-scale UAM services in the United States subject to these constraints.

Seven potential scaling constraints are identified through exploratory case studies of UAM operations in three U.S. cities. Of these constraints, the development of takeoff and landing areas (TOLAs) and the provision of air traffic control (ATC) services are proposed as principal near-term constraints and selected for detailed analysis.

The development of high-throughput, small-footprint TOLAs to enable UAM scaling in urban areas is evaluated as a multicommodity flow problem. TOLA design and aircraft performance attributes that enhance throughput per footprint are determined through tradespace analysis. TOLA throughput is found to be highly dependent on attributes of ATC, namely controller workload and separation minima. Estimates of maximum aircraft throughput capacity are developed for representative inner-city UAM TOLAs of various physical designs.

The development of procedurally segregated airspace cutouts for UAM flight is shown to be a promising strategy to enable high-volume UAM operations within terminal airspace. Furthermore, four flight procedures are proposed to support UAM access to commercial airports under both instrument flight rules (IFR) and visual flight rules (VFR). Lastly, the magnitude of ATC restrictions on the scale of UAM operations is evaluated in the 34 largest U.S. metropolitan areas. The degree to which ATC may constrain UAM scale is found to vary widely between these metropolitan areas potentially inhibiting service to over 75% of the population in the most restricted city but less than 15% in the least restricted city. The development of airspace cutouts for VFR UAM operations reduces this variation and increases population coverage from 65% to 80% in the median U.S. metropolitan area.

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They say it take a village to raise a child, and considering how much unbounded energy I had that's probably true. But to mint a Ph.D. I'm estimating the personnel requirements are on the order of a small city-state, or at least a major multinational research institution. Thanks MIT for taking that burden off my folks.

The cast of characters who I owe this accomplishment to truly does span the globe. It was through Jungwoo, Val, and Vishwa's willingness to get on phone calls spanning 17 time zones that chapter 9 began to solidify in my mind. Ken Goodrich, Michael Patterson, and Kevin Antcliff from NASA Langley were instrumental in not only guiding my research to this conclusion, but even more so for helping me to navigate the UAM industry and identify exciting collaboration opportunities. I am especially appreciative to Brendan Reilly and Andy Hale from the FAA who lent me their time and extensive experience as tower controllers to make Chapter 8 rooted in reality. Not only did they have an answer to every question I had, but usually it came with a far more exiting tale of aviators past and present. On the subject of Chapter 8, I appreciate the support of the Airport Cooperative Research Panel and my advisory panel consisting of Larry Goldstein, Rich Golaszewski, Monica Alcabin, David Ballard, and Colleen Reiche.

The backbone of any Ph.D. student's experience is their committee. I am especially grateful to Chris Zegras for taking a chance on me to help me consider UAM from the perspective of an urban planner and our cities. Although we did not get to dive into some of the more fascinating policy and implementation questions for UAM over the course of this thesis, I am hopeful that Chris and I will have that opportunity in the future. I owe much of Chapter 5, especially the more quantitatively rigorous bits, to Hamsa Balakrishnan. Her advice was critical to move my research from a loose set of concepts to an actual thesis. I will forever be indebted to Amedeo Odoni who graciously stepped into the role of external evaluator for my Ph.D. proposal defense (15 minutes into the presentation, mind you) after a conflict arose for the original evaluator. This happenstance interaction led to a whole new avenue of research resulting in Chapter 8. The efforts of my two thesis readers, Brian German and Michael Patterson (he pulled double duty here), were especially helpful as I geared up for my defense and wrapped up this document. I hope to continue working with each of them throughout my career.

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Finally, it was only through the Lord's plan and by his hand that I completed this task. May this Ph.D. set me on a path to continue his good work.

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For Jim, Debra, Brittany, and Audrey

None of this would have been possible without family.

Table of Contents

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1 Introduction

Over half of the world's population currently lives in cities, and by 2050 this percentage is expected to exceed two thirds. As a result, cities are getting larger. Between 1990 and 2018 the number of cities with more than 10 million inhabitants, known as "megacities," increased threefold from 10 to 33. By 2030 there may be as many as 43 megacities and over 700 cities with more than one million residents [1].

With increased urbanization comes an increased need for transportation in terms of passenger and cargo volumes, geographic coverage, speed, and environmental efficiency. To meet this need, cities are investing in traditional modalities including rail, automobiles, micromobility[1], and bus services [2,3]. However, these surface transportation modes are hindered by decaying legacy infrastructure, community restrictions to new development, and ever-increasing congestion.

Urban air mobility (UAM) is a concept that proposes to develop short-range, point-to-point transportation systems in metropolitan areas using vertical takeoff and landing (VTOL) or short takeoff and landing (STOL) aircraft. UAM aims to provide trips on the sub-regional scale, such as flights between nearby cities, flights to and from the suburban or rural areas around a city, or even flights within the urban core of a single city.

Although previous helicopter-based passenger services provided aerial transportation similar to UAM, the services did not achieve long-term viability due to issues including fatal accidents, noise restrictions, and financial challenges. Proponents of UAM anticipate that recent advancements in aircraft electrification, automation, telecommunications, and business models driven in part by unmanned aircraft system (UAS) and automobile applications may mitigate these challenges [4,5]. Fig. 1 presents examples of three out of over 200 announced aircraft designs intended to provide UAM services.

Joby Aviation *EHang* *Lilium Aviation*

Fig. 1 Example aircraft proposed for use in urban air mobility.[2]

A concern for UAM is the feasible *scale* of operations that these networks may achieve. This thesis defines the "scale" of a UAM network as the number of passenger or cargo trips that may occur within a specified geographic region in a reference time period; the geographic region may be as large as a metropolitan area or could be as small as a single neighborhood.

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[1] Micromobility includes conventional or electrified bicycles, scooters, skateboards, or other similar systems

[2] Images from Joby Aviation: www.jobyaviation.com, EHang: www.ehang.com, & Lilium Aviation: www.lilium.com

While new aircraft are anticipated to provide noise, cost, emissions, and safety benefits compared to legacy helicopters and aircraft, it is unclear if these improvements are sufficient to make large-scale UAM services feasible. Furthermore, it is also unclear how city-to-city differences will affect the scalability of UAM networks irrespective of the aircraft technologies in use.

1.1 Objectives and Hypothesis

The objectives of this thesis are to: (1) evaluate UAM operations to identify its principal scaling constraints, (2) discern how the severity of these constraints varies with different implementation locations and operational concepts, and (3) assess the feasibility of large-scale UAM services in the United States subject to these constraints.

The hypothesis is that conventional air traffic control services will significantly constrain the near-term scalability of UAM services in most large cities, and that the severity of this constraint may be partially relieved through the application of existing airspace and procedure design strategies.

The methods and findings presented within the thesis inform technology developers, operators, regulators, and city planners of the constraints for large-scale UAM implementation, promising opportunities to mitigate the constraints, and the attributes of cities that are well-suited to support initial UAM services.

1.2 Scope

This thesis defines UAM as a sub-regional air transportation service for passengers or cargo that leverages aircraft with STOL or VTOL capabilities to operate from infrastructure with a footprint that is significantly less than conventional airports. Under this definition, conventional helicopter charter services are considered representative of UAM.

The analysis of UAM in this thesis focuses on the United States' ecosystem for flight. UAM operations may be affected by numerous attributes that vary between countries, including air traffic control, community tolerance of aviation operations, and electricity grid reliability, among others.

Current-day characteristics of the aviation system and metropolitan areas are assumed as the baseline for the analysis of UAM scaling. For example, the scaling constraints are based upon existing customer demand patterns, existing airport or heliport infrastructure, current air traffic control policies, and current air traffic volumes. Opportunities to relieve these constraints through strategies such as new infrastructure or automation are then assessed from this baseline.

1.3 Outline

Prior air transport services similar to UAM are first reviewed to discern why these systems were unable to achieve sustainable, large-scale operation. Next, exploratory case studies of hypothetical UAM operations in three cities are developed to identify potential scaling constraints for the service. The outcome of the city case studies leads to the proposal of takeoff and landing area (TOLA) availability and air traffic control (ATC) services as key scale-limiting constraints for UAM.

The body of this thesis develops a detailed understanding of how these two constraints may influence the feasible scale of UAM operations. Strategies to lessen the severity of the constraints and enable UAM scaling are evaluated. Finally, the concluding chapter estimates the magnitude of ATC restrictions on UAM scale in 34 major cities across the United States and demonstrates the effectiveness of the proposed mitigation strategies.

Fig. 2 provides an overview of the thesis contents.

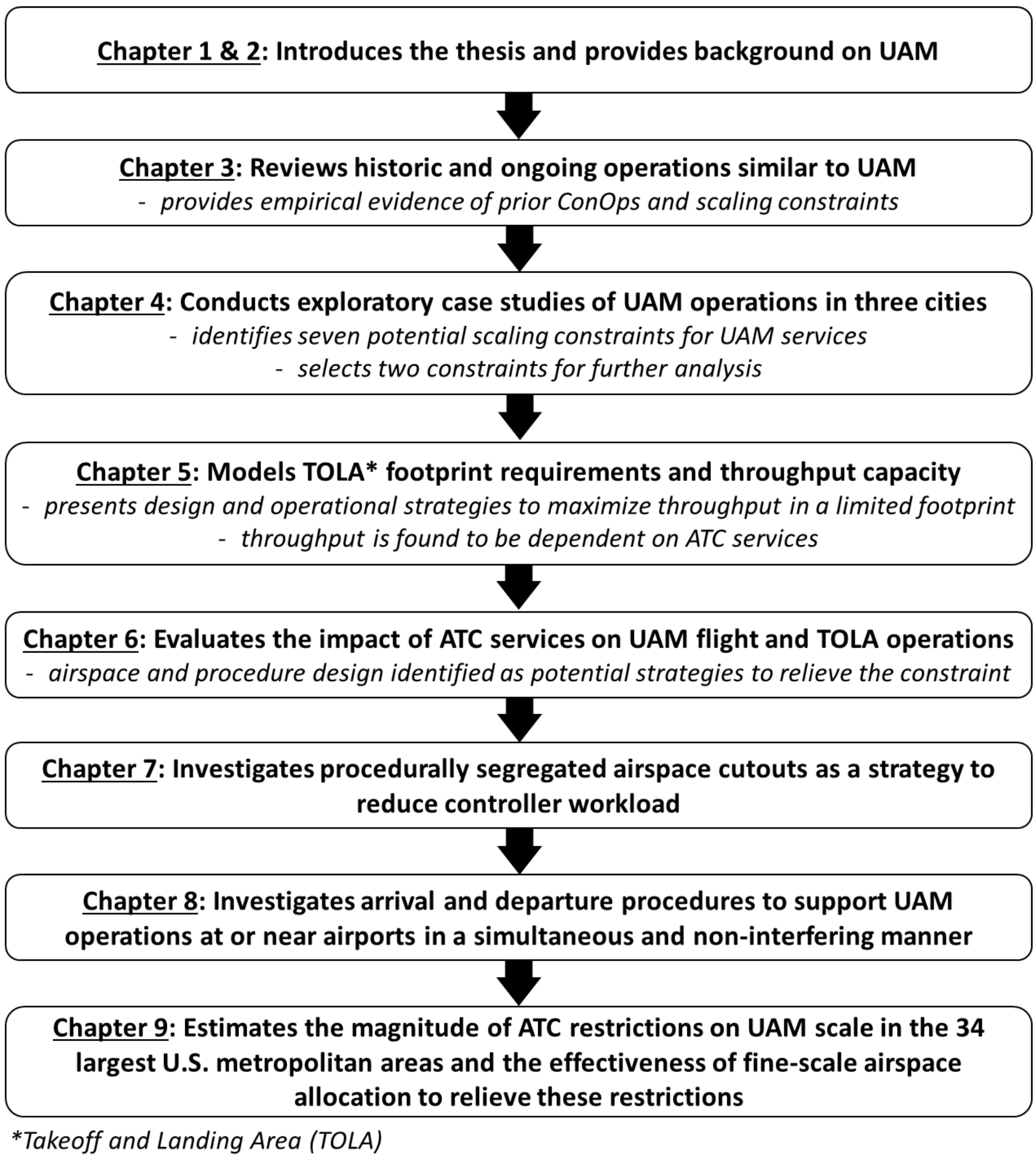

Fig. 2 Overview of the thesis contents.

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2 Background on Urban Air Mobility

This chapter provides an overview of the concept of operations, markets, enabling technologies, and aircraft proposed for UAM. A detailed history of UAM and the lessons learned through prior operations and research is provided in Chapter 3.

2.1 The Concept of Urban Air Mobility

Urban air mobility broadly refers to a variety of related concepts for aircraft-based transportation systems that provide services within or in proximity to a core metropolitan area. Fig. 3 displays three UAM service concepts proposed in the literature.

Intra-urban and airport services involve trips in the immediate vicinity of a city and its surrounding settlements [5–7]. Inter-urban "thin-haul" services refer to longer, sub-regional trips between city centers that either do not have a commercial aviation route, or for which the UAM service may compete with the existing commercial route [8–10]. All three UAM services compete for customers with other transportation modes through cost and/or convenience. Convenience may consist of many factors, such as faster door-to-door travel, travel on a preferable schedule, or travel with reduced hassle.

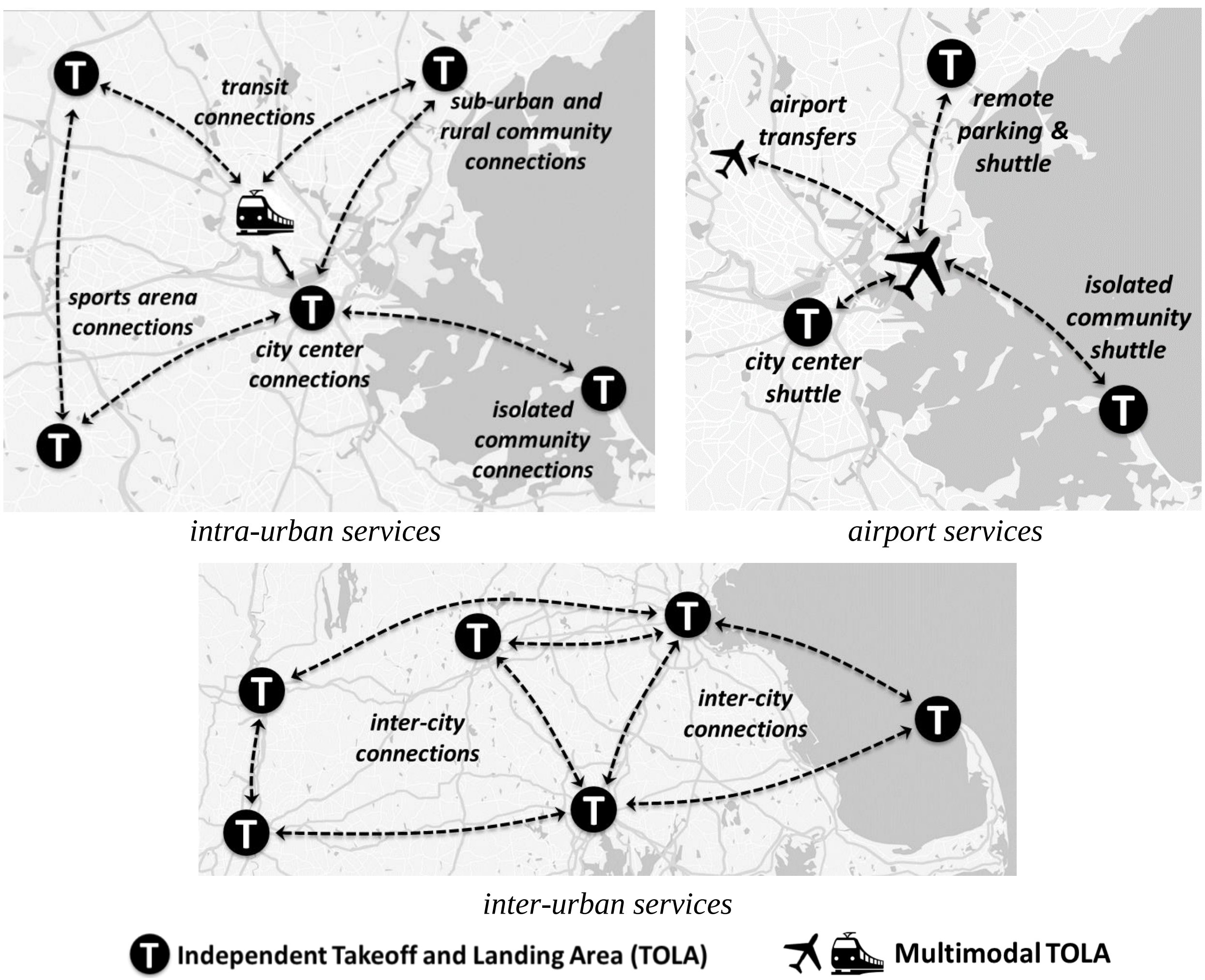


Fig. 3 Three service types proposed for UAM services.

The three UAM service types introduced in Fig. 3 may require aircraft and infrastructure that are quite different from one another in order to meet the unique needs of their missions. A number of prior operators and researchers evaluated these requirements for various UAM concepts. Table 1 displays twenty different variations of UAM that explored the use of helicopters, powered-lift vehicles, and STOL aircraft to support one or more of the UAM service types introduced in Fig. 3. The authors' original names for each concept are maintained in Table 1, and many of the concepts are closely related or identical (such as on-demand air service and on-demand aviation).

The helicopter air carriers were the first and largest example of UAM, to date, in terms of annual passenger volumes. These operators primarily provided airport shuttle services. Charter air taxi services (either by helicopter or aircraft) are the longest running form of UAM and provide all three service types. The concepts in the 2000 to 2008 era generally proposed to use fixed-wing aircraft for inter-urban thin haul services. Finally, the numerous concepts since 2010 have mostly focused on the use of VTOL capable aircraft (often electrically powered) for the intra-urban and airport services.

Table 1. Concepts for short-range, aircraft-based transportation systems similar to UAM.

Concept	Active Dates	Reference
Helicopter Air Carrier	1953 - 1976	[11,12]
Air Taxi	1962 - present	[11–13]
Metrotaxi/Metrobus	1970	[12]
Intracity Air Transportation	1970	[12]
Interurban Short Haul Air Transportation	1973	[14]
Personal Air Transportation	2003 - 2006	[15,16]
On-Demand Air Transportation	2005, 2012, 2017	[17–19]
On-Demand Air Service	2008	[20]
On-Demand Aviation	2010 - 2018	[21–25]
On-Demand Air Mobility	2012, 2016	[8,26]
Zip Aviation	2012 - 2014	[27,28]
Sky Transit	2015 - 2017	[29,30]
On-Demand Mobility	2006, 2015 - present	[31–34]
Thin-Haul	2015 - present	[9,10,35,36]
Air Mobility on Demand	2016	[37]
Urban Air Transportation	2016 - present	[5,38]
Urban Air Mobility	2016 - present	[39–41]
On-Demand Mobility for Aviation	2017	[42–44]
Aerial Ridesharing	2017 - present	[45]
Sub-Urban Air Mobility	2018 – present	[46]

Greater detail on these prior UAM concepts is provided in Chapter 3. This thesis jointly evaluates operational scaling for the three service types displayed in Fig. 3. Despite operating over different mission ranges and potentially utilizing aircraft with different configurations, the general operating paradigm for the service types is the same. For example, each service type shares the need for aircraft to enter congested airspace near cities without disrupting conventional flight operations, access TOLAs sited within urban areas near demand, and provide high-frequency flights.

2.2 Concept of Operations

Fig. 4 summarizes a generic mission concept of operations (ConOps) representative of any of the three UAM service types presented in Fig. 3. The acronym "TOLA" stands for "takeoff and landing area" and refers to any location from which or to which a UAM aircraft may arrive or depart including, but not limited to, airports, heliports, vertiports, and unimproved landing areas.

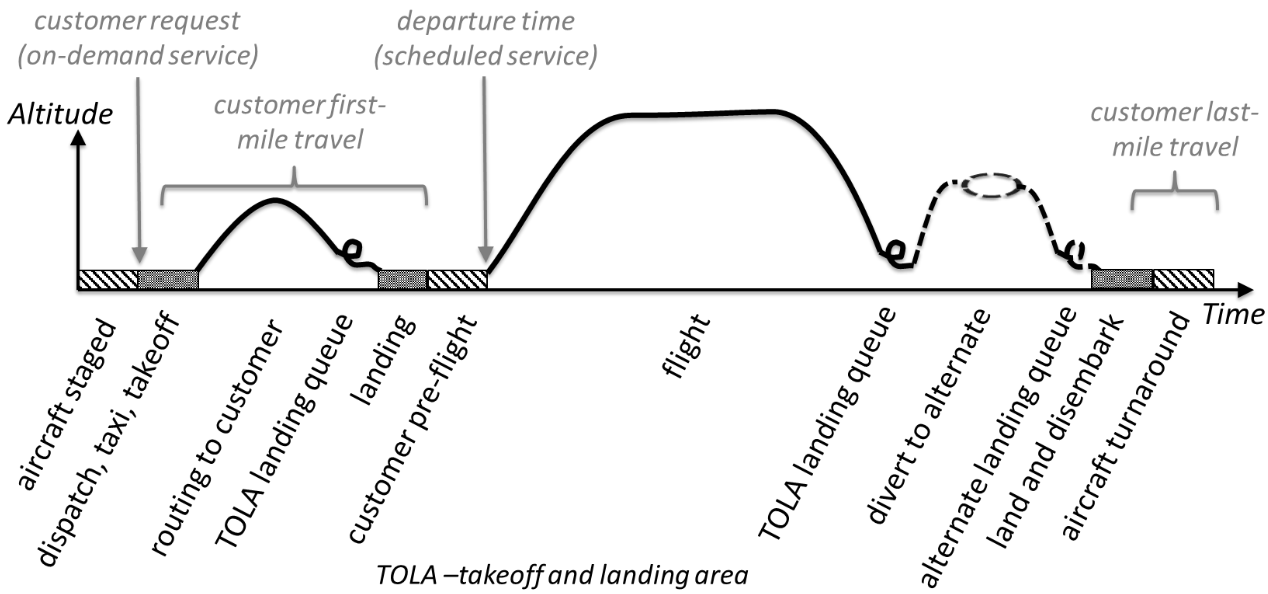


Fig. 4 Generic UAM mission ConOps.

The ConOps is initiated either when a customer submits a travel request, or when a scheduled departure time is at hand. At this point an aircraft and the customer must both be routed to the origin TOLA. The customer conducts first-mile surface travel to the TOLA using an available transportation mode. If an aircraft is pre-positioned on-site, then a flight crew may be assigned to the aircraft and begin flight planning and preparation. If an aircraft is not available on-site, then a nearby vehicle may be ferried to the origin TOLA.

Once the customer arrives at the origin TOLA, they may be required to conduct activities such as a security screening, safety briefing, and luggage check before boarding the aircraft and initiating the cabin pre-flight activities.

The flight segment of the ConOps is then conducted requiring pilot (or autonomy) interactions with flight dispatch, air traffic control, and weather products, among other support services. The aircraft may be required to hold or divert if the destination TOLA is congested or inaccessible due to factors such as inclement weather, a disabled aircraft, or an emergency. Once the aircraft arrives, the customer conducts the last-mile surface transportation to their destination. The aircraft is then turned (involving activities such as fueling/charging, cleaning, and flight crew rotation) before it is prepared for another mission.

The scalability of a UAM network is dependent upon how quickly each step of the UAM mission ConOps may be conducted, and how many aircraft may conduct each step of the ConOps in parallel. For example, throughput at a given TOLA may be increased by reducing the amount of time it takes a given aircraft to approach, land, turnaround, and depart. Alternatively, throughput at the TOLA may also be increased if multiple aircraft may simultaneously conduct these activities.

2.3 Potential Role of UAM in Urban Transportation

The primary market driver for new transportation options such as UAM is increasing congestion in cities. Current roadways and railways are increasingly congested as cities expand and this legacy infrastructure ages and degrades. Furthermore, the introduction of ridesharing services has worsened congestion by adding more trips to the roads [47,48]. Autonomous cars may further increase congestion by inducing new demand, especially trips with no passengers [49–52]. Finally, the development of additional road capacity has been shown to provide no relief to congestion in the long run suggesting outlying communities may not be made more accessible by adding capacity to current highways [53,54].

Sub-regional air transportation may complement existing automobile and public transportation by providing increased capacity without exacerbating surface congestion. Furthermore, movement by air provides unique capabilities compared to surface modalities that may enable UAM to access underserved markets or enhance the transportation mix of a given city; these capabilities include:

1. Obstacle Overflight: The ability to overfly surface congestion or geographic obstacles (e.g., water bodies, wilderness areas, and mountains) enables UAM to more directly and rapidly connect two locations. Overflight also enables new transportation services to be provided at locations where expansion of the existing surface modes may not be possible. As urban growth continues, UAM may provide consumers and companies with newfound access to areas of lower land value either outside the urban core or in historically difficult to reach areas, such as islands.

2. Faster Transport: The higher cruise speed of aircraft compared to most surface modes enables UAM to rapidly connect rural communities, outlying airports, or settlements on the periphery of a metropolitan area to the central business district (CBD). However, long first-mile or last-mile surface transportation requirements to or from a TOLA may diminish the advantages of higher flight speeds for UAM customers.

3. Nodal Infrastructure: Aviation infrastructure is *nodal* in nature. This means that for an aircraft with sufficient performance, each TOLA in a region is directly connected to every other TOLA in the region even though a physical link does not exist. This quality is in contrast to road or railway infrastructure which are *linear* in nature. Linear infrastructure requires a continuous physical connection between places in order to connect them. The nodal nature of UAM TOLAs increases the adaptability of the system. New TOLAs added in new markets are directly connected to the rest of the UAM network. Furthermore, nodal infrastructure increases network resiliency in some scenarios where linear transportation systems may be degraded. In some natural disaster or maintenance scenarios, UAM may continue to operate when other transportation systems are down. UAM systems may also continue to operate when a subset of TOLAs are offline.

Despite these opportunities, UAM systems may not be advantageous to a city's transportation portfolio if the scale of the service is small or if the negative externalities of the service outweigh its benefits. Prior work by the author on page 304 of reference [42] introduced a number of negative externalities potentially associated with UAM; these include environmental impacts from aircraft operation or increased urban sprawl, intensified socio-economic segregation, and displaced ridership for public transportation.

In terms of UAM system scale, according to the American Public Transportation Association the three largest U.S. cities (New York, Los Angeles, and Chicago) transport a combined 10 million passengers by rail and four million passengers by public bus each day [55]. In comparison, the largest prior UAM systems moved an estimated combined maximum of 3400 passengers per day (1.2 million per year) in these same three cities by helicopter [12]. If new UAM systems are unable to provide services at a significantly increased scale than these prior helicopter airlines, then UAM may be limited to serving limited routes and elite customers potentially compromising the social value of the service.

2.4 UAM Market Size and Feasible System Scale

Numerous researchers have attempted to estimate the size of the U.S. and global markets for UAM. However, these predictions generally estimated the *total addressable market (TAM)* for UAM by assuming that an unconstrained number of flights may be provided at the assumed price point. Prior research by MIT [42,43] and Booz Allen Hamilton [6] determined that operational limitations such as ATC, TOLA availability, and pilot staffing could constrain the feasible scale of operations and limit the *serviceable addressable market (SAM)* to a fraction of the TAM. An objective of this thesis is to more accurately predict the achievable scale of UAM services in a given city in order to support the estimation of the SAM.

A brief review of key UAM market studies is provided below with a discussion of noted scaling barriers that may constrain the TAM.

First, a study sponsored by NASA Langley in 2012 reviewed notional air taxi services using small aircraft [19]. The work found that a projected trip demand of over 100 million passengers could be achieved annually with technologies anticipated to be available in 2035 if the cost per seat-mile was roughly one dollar baselined with 2000 dollars (approximately $1.49 in 2019 dollars) [19,22]. The study identified that the number of operations required to fulfill this TAM would exceed the capacity of ATC generating untenable delays for both conventional and UAM traffic. Furthermore, the study noted that this scale of UAM would exceed the capacity of 200 airports in their simulation and require “significant upgrading of existing facilities and building of new facilities” to capture the projected TAM [19].

Next, in 2014 Virginia Tech researchers developed a multinomial logit mode choice model which included hypothetical electric air taxi services from existing airports and heliports. Their work suggested that UAM aircraft operating at $1.00 and $0.50 per seat-mile (approximily $1.09 and $0.54 in 2019 dollars) could capture as many as 21,000 and 121,000 passenger trips per day, respectively, in the New York metropolitan area [28]. This study assigned a constant delay to all flights to account for congestion, but did not consider how delay may increase with scale or if any capacity limits would be reached at these flight densities.

An initial attempt to estimate SAM for UAM services was conducted in 2017 by Virginia Tech [56]. The analysis not only considered markets and vehicle operating costs, but also evaluated a variety of operational factors including landing fees, air traffic control routing, and TOLA throughput capacities. The analysis found that if UAM costs are between $1.0 and $1.25 per seat-mile, then roughly a 4% market share (320,000 commuting passengers per day on 133,000 flights) could be achieved in Northern California. For perspective, the ten airports in the San Francisco Bay Area currently support an average of 5000 flights per day. Virginia Tech noted that weather conditions and public acceptance of UAM services were not included in the analysis and may impact the feasible scale of operations further reducing the predicted SAM [56].

A variety of recent market studies also attempted to distinguish between TAM and SAM for UAM by considering constraints such as infrastructure availability, vehicle production rates, and weather. A 2018 Booz Allen Hamilton study for NASA estimated the U.S. TAM at $500 billion, but predicted that the near-term SAM would be on the order of $2.5 billion annually due to scaling constraints [6]. A similar study by Porsche Consulting estimated the global TAM in 2035 at $230 billion annually, of which $21 billion is anticipated to be serviceable [7].

These studies suggest that operational constraints will have a significant effect on the UAM market potential reducing the SAM to a small percentage of the TAM. If UAM services may be provided at price points near those proposed in these studies, then near-term UAM services are likely to be supply constrained by operational constraints as opposed to demand constrained. This thesis strives to develop a better estimation of the impact of the key operational constraints on feasible UAM service scale.

2.5 Impact of Emerging Technologies on UAM Scaling

Although various forms of UAM have been attempted over the past century, these efforts have not led to a sustainable system of significant scale. Today, a handful of emerging technologies may provide new vehicle and system capabilities that will overcome historical scaling constraints.

2.5.1 Electric Propulsion

Piston and jet airplanes or helicopters have previously experienced throughput limitations in urban areas due to large airport footprints (for airplanes), safety concerns, and noise or gaseous emissions.

The development of increasingly miniaturized, capable, and affordable electric aircraft components driven by the UAS and automobile industries have opened a new design space for electric and hybrid-electric passenger carrying aircraft. In particular, the concept of distributed electric propulsion (DEP) may reduce runway requirements for STOL aircraft, increase the cruise speed of VTOL aircraft, and improve the cruise efficiency for either type of aircraft. DEP may therefore enable new UAM aircraft that operate from TOLAs with footprints similar to helipads.

Furthermore, electric propulsion is proposed to increase reliability, improve aircraft safety, reduce emissions, and reduced noise compared to conventional helicopters thus addressing a variety of prior challenges faced by UAM operators [4,9,10,57]. However, electric aircraft pay significant weight penalties due to the limitations of energy storage technologies, may require increased turnaround time for charging, and do not yet have a clear certification pathway.

2.5.2 Flight Automation

Piloting requirements may impact feasible UAM scale due to the difficulty of hiring sufficient pilots, as well as the costs associated with their service. Increasing levels of automation on the flight deck and in the aviation system may reduce piloting training requirements and cost, or perhaps even enable minimally trained civilians to safely operate an aircraft [10,21]. The General Aviation Manufacturers Association (GAMA) recently detailed the development progress of technologies to support simplified vehicle operations and proposed pathways to implement these capabilities [58].

Similarly, air traffic controller workload limitations may constrain UAM scale in some high-density airspace. Increasing levels of decision support or automation of ATC, such as under development by NASA's UAS Traffic Management program, may also reduce controller costs and constraints on UAM scale [59].

2.5.3 Telecommunications

Pervasive telecommunications connectivity presents a variety of novel opportunities for UAM providers to overcome demand management and ATC challenges historical UAM operators experienced. First, the automobile industry has demonstrated the power of smart-phone or web-based applications to support the real-time management of supply and demand in ride-sharing networks. This capability may more efficiently manage UAM logistics and increase throughput.

Furthermore, the near universal coverage of telecommunications networks and the interconnection of many devices through the internet of things (IOT) provides emerging UAM systems with new options for communication, navigation, and surveillance (CNS) in low altitude airspace. ATC has historically experienced difficulty providing services to aircraft flying at low altitude in urban areas [60]. As a result, ATC has imposed throughput restrictions to prevent flight conflicts and ensure safety in these areas. One such example is at uncontrolled airports where only one aircraft is authorized to simultaneously conduct an instrument arrival or departure because ATC cannot ensure radar separation. This one-in, one-out operation limits throughput compared to airports with greater CNS equipage. UAM operations that are augmented by the telecommunications and IOT infrastructure may enable higher flight densities in airspace such as this.

2.6 Potential Scaling Impacts of Aircraft Configuration

The emergence of viable full-electric and hybrid-electric propulsion systems for small aircraft has resulted in the development of aircraft with non-standard configurations (i.e., configurations other than conventional rotorcraft or fixed-wing aircraft with one to three propulsors) [38]. Three such non-standard configurations are multirotor, powered-lift, and blown-wing aircraft.

Multirotor aircraft use numerous propulsors to generate vertical lift and differential thrust to enable translational movement. This is in comparison to helicopters which typically use one large rotor for lift and cyclic control of the blades to enable translation. The first row of Table 2 displays an example multirotor aircraft. Helicopter and multirotor aircraft are both types of rotor-lift vehicles.

Blown-wing aircraft distribute numerous propulsors along the span of the wing in order to enhance aerodynamic performance compared to a conventional fixed-wing aircraft. Jet powered aircraft may use nozzles to directly blow air over the rear edge of the wing for a similar effect. Row 2 of Table 2 provides an example of a notional blown-wing aircraft for UAM.

Powered-lift aircraft generate vertical lift through either an independent propulsive system or the vectoring of thrust from the forward-flight propulsors. Numerous powered-lift concepts have been developed with different mechanisms to achieve vertical lift as displayed in the remaining rows of Table 2. Many powered-lift aircraft have a wing to improve the efficiency of forward flight.

Prototypes of powered-lift, multirotor, and blown-wing aircraft were flown as early as the 1950s. However, these exotic configurations were burdened by large weight, cost, and safety penalties associated with the limitations of mechanical drive systems, materials, and control systems at the time. Distributed electric propulsion and other technologies may now enable feasible aircraft of these configurations and provide new performance capabilities to the UAM mission.

Table 2 presents a comparison of the new generation of electric or hybrid electric UAM aircraft to similar concepts that used conventional propulsion. Potential ramifications of the different configurations for UAM system scaling are discussed in the subsections following Table 2.

Table 2. Comparison of 2020-era hybrid and all-electric aircraft with 1960-era conventionally powered aircraft of similar configuration (1 of 2).

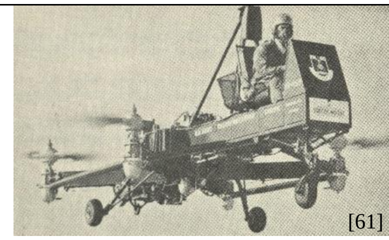
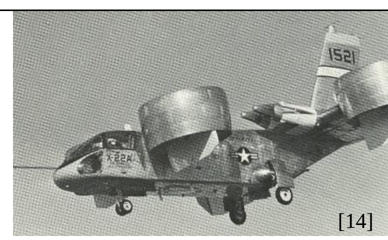
Rotor-Lift: Multicopter *Left:* Volocopter GmbH VC200 First flight 2013 *Right:* Curtiss-Wright VZ-7AP First flight 1958	 *www.volocopter.com*	 [61]
Winged-Lift *Left:* MIT super-STOL concept 30% scale prototype flight in 2019 *Right:* Helio Aircraft Co. Helio Courier First flight 1949		 *www.aviastar.org*
Powered-Lift: Tilt-Wing *Left*: Airbus A^3 Vahana First flight 2018 *Right:* Ling-Temco-Vought XC-142 First flight 1964	 *www.airbus-sv.com*	 [14]
Powered-Lift: Tilt-Duct *Left:* Bell Nexus No first flight *Right:* Bell X22-A First flight 1966	 *www.bellflight.com*	 [14]
Powered-Lift: Tilt-Prop/Rotor *Left:* Karem Aircraft Butterfly No first flight *Right:* Curtiss-Wright X-19 First flight 1963	 *www.karemaircraft.com*	 *www.globalsecurity.org*

Table 2 (continued). Comparison of 2020-era hybrid and electric aircraft with 1960-era conventional aircraft of similar configuration (2 of 2).

<u>Powered-Lift: Compound Heli.</u> *Left:* Carter Aviation Tech. & Mooney Intl. CarterCopter; No first flight *Right:* Fairey Rotodyne First flight 1957		
<u>Powered-Lift: Lift + Cruise</u> *Left:* Kitty Hawk Cora First flight 2017		*No Comparative Historical Concept Identified*
<u>Powered-Lift: Tail Sitter</u> *Left:* NASA Puffin No first flight *Right:* Lockheed XFV-1 First flight 1954		

2.6.1 Rotor-Lift Configurations

Conventional helicopters have sufficient performance capabilities to meet the requirements of the UAM mission profile. However, historical helicopter public transportation networks did not sustainably achieve large-scale operations due to high operating costs, objectionable noise, and poor safety records. Current helicopter operations also continue to be scale-constrained in many U.S. markets primarily due to noise. Annoyance from helicopter noise led Congress to direct the FAA to reduce noise impacts in Los Angeles in 2013 [62], prompted the New York City Council to reduce the number of helicopter tours by half in 2017 to 30,000 annual flights [63], and led to the closure of the majority of heliports in San Francisco.[3]

Electrification of the helicopter configuration does not remove the collective and cyclic blade pitch controls. These complex controls represent numerous single points of failure for helicopters and result in high manufacturing, certification, and maintenance costs. Furthermore, while electrification may remove the noise component associated with the combustion engine, the main rotor and tail rotor are significant noise generation sources on helicopters and would be unaffected by electrification. Finally, rotor-lift configurations have increased energy requirements compared to wing-borne flight during cruise and potentially lower maximum speeds [38,64].

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[3] http://www.stophelipad.org/helipads.shtml.

The multirotor configuration has the advantage of reducing mechanical complexity (and thus cost) compared to the helicopter. Through the use of differential thrust between the numerous motors, fixed-pitch and non-articulating rotors may potentially be used on multicopter instead of the complex cyclic controls on a helicopter. Not only do these simplifications reduce the complexity of each rotor, but the redundancy between multiple rotors also relieves each from representing a single point of failure for the aircraft. Finally, smaller rotors may also be operated at lower tip speeds to lessen noise generation.

In terms of UAM scaling, both of the rotor-lift configurations may benefit from special operating allowances by ATC including reduced separation minima and lower VFR visibility requirements. Helicopter currently receive these allowances while fixed-wing aircraft do not as a result of their lower speeds, higher maneuverability, and ability to hover. Rotor-lift vehicles also may conduct VTOL operations to reduce TOLA footprint and increase siting opportunities. However, the noise, energy, and speed limitations of rotor-lift configurations may negatively impact their ability to provide large-scale UAM services.

2.6.2 Winged-Lift Configurations

Winged-lift STOL aircraft, either with conventional or distributed propulsion, may be advantageous for the UAM mission in that they have clearer certification pathways, have fewer critical failure modes (e.g., are typically capable of unpowered controlled descent by a human pilot in the case of propulsion system failure), exhibit reduced energy requirements, and may generate less noise compared to vehicles with VTOL flight segments [41,65]. The critical scale-constraining attribute of winged-lift configurations, however, is the larger infrastructure footprint required for STOL facilities compared to VTOL facilities. Runways on the order of a few hundred to a thousand feet have limited siting opportunities in urban areas and a lower aircraft throughput per footprint.

The second row of Table 2 displays a hybrid-electric, blown-wing aircraft concept developed by MIT and a conventionally-propelled STOL aircraft from the 1950s called the Helio Courier. The primary benefit of electrification for fixed-wing aircraft is to increase the lift coefficient of the wing through blowing to provide enhanced short-field performance. While the Helio Courier had a takeoff distance around 600 ft, the MIT STOL concept is anticipated to have a ground roll on the order of 100 ft with a similar payload capacity [41]. This significant reduction in ground roll may enable aircraft of the blown-wing configuration to operate from similar infrastructure as VTOL aircraft and mitigate the infrastructure scaling challenge for the winged-lift aircraft configuration.

2.6.3 Powered-Lift Configurations

The remaining rows of Table 2 display numerous configurations for powered-lift vehicles including tilt-thrust (tilt-wing, tilt-duct, tilt-rotor, vectored thrust, etc.), compound helicopter, lift + cruise, and tail sitter configurations. The primary operational benefit of the powered-lift configuration is to provide efficient wing-borne cruise and either STOL or VTOL capabilities. The differences between the various powered-lift configurations may also accentuate other attributes of the aircraft. For example, tilt-duct aircraft may provide reduced noise emissions due the shielding of blade noise and the reduction of tip vortex interactions. Compound helicopters may increase hover efficiency through the use of large rotors with low disk loading. Finally, researchers at Cornell have predicted that tilt-wing and lift + cruise configurations have improved long-range performance compared to rotor-lift aircraft and the tilt-rotor configuration [64].

In terms of UAM scaling, powered-lift aircraft may provide the key advantages of both the rotor-lift and winged-lift configurations. Powered-lift aircraft may operate with VTOL to reduce infrastructure footprint. They may also potentially leverage the ATC allowances for reduced separation and weather minima afforded to helicopters because they may also have the ability to hover. Furthermore, wing-borne cruise will enhance the energy efficiency of the flight for longer range missions while also reducing the noise generated in cruise.

Historically, powered-lift aircraft have been technically challenged due to the limitations of combustion engines and mechanical powertrains. These systems required numerous gearboxes and drive shafts that increased the complexity of the powered-lift aircraft on the right of Table 2 resulting in higher costs, reduced safety, and increased maintenance. However, electrification of the aircraft powertrain may reduce this complexity.

However, powered-lift aircraft may also be susceptible to a number of operational limitations. The combination of helicopter and fixed-wing components and flight regimes may complicate pilot certification and staffing for these aircraft. The additional weight required to provide both rotor-borne and wing-borne flight modes may reduce energy efficiency compared to the pure winged-lift configurations. Finally, the certification pathway for powered-lift aircraft is less clear than for either of the other configuration families.

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3 Historic and Current Urban Air Mobility

This chapter provides a review of the historical development of UAM systems, the attempts to implement them, and the factors that inhibited their ability to scale or remain in operation. The lessons learned through these previous efforts provide insight into the current-day challenge of designing and implementing large-scale UAM systems.

3.1 Chapter Overview

Section 3.2 provides a brief discussion of the operational history of helicopter airlines in the "golden age" of helicopters during the 1950s, 60s, and 70s. These networks provided the largest scale of UAM operations to date, but did not achieve long-term viability. Section 3.3 reviews a variety of VTOL development programs, charter networks, and taxi services that existed between 1980 and the early 2000s.

Section 3.4 discusses the small aircraft transportation system (SATS) and very light jet (VLJ) efforts of the 2000s. These systems generally concerned flights of longer range than considered in UAM, however their efforts resulted in the development of numerous weather-tolerant vehicle, piloting, and air traffic control technologies relevant to UAM. Finally, section 3.5 introduces the operation of three on-demand helicopter networks. Recent literature on UAM systems is also introduced.

The precursor industries and technologies developed through each of these efforts constitute the historical underpinnings for modern UAM. It is notable that the general concept of UAM has emerged four distinct times over the past 70 years, with each iteration being associated with a new vehicle technology: 1960s – helicopters, 1980s – tiltrotors, 2000s – VLJs, 2010s – electric VTOLs (eVTOLs).

However, in each of the three previous iterations the new vehicle did not turn out to be a panacea for the scaling challenges of urban air transport. In each case, operational, regulatory, and/or economic factors ultimately prevented the systems from providing sustainable, large-scale operations. The challenges these previous operators experienced inform the scaling constraints evaluated in this thesis.

3.2 Helicopter Airlines from 1950 to 1980

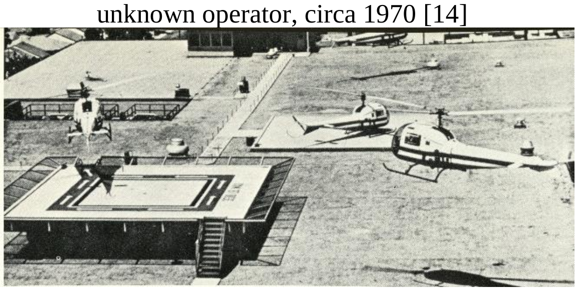
This thesis proposes that the helicopter airlines of the mid-20th century had a ConOps similar to current UAM proposals. Their services demonstrated UAM operational capabilities such as TOLA footprint size and throughput capacity, aircraft inter-arrival spacing, and airport integration strategies, to name a few. Furthermore, the scaling constraints the helicopter airlines experienced are also likely to challenge current-day UAM networks.

The first commercial helicopter air transportation company carried passengers beginning in 1953 to and from New York City's three major airports; services into Manhattan began in 1956. Within a decade scheduled helicopter carriers were also operating in Los Angeles, San Francisco, and Chicago. These companies primarily provided connecting services between major airports or between airports and nearby city centers. Operations grew from under 155,000 annual helicopter passengers in 1957 to over 1.2 million passengers in 1967 [12].

In addition to these four scheduled urban air carriers (one in each city above), over 100 helicopter-based air taxi operators also emerged providing pre-booked, intra-city charter transportation [11]. One of these operators, "Air General," set up a network of over 70 heliports in Boston (many in parking lots or private greenspaces) and provided a commuter service from 1962 to 1969 carrying more than 100,000 passengers over that period [12].

Table 3 displays the infrastructure and aircraft used by the historic helicopter airlines juxtaposed with currently proposed UAM concepts.

Table 3. Comparison of 1960-era UAM operations and current UAM concepts.

Single helipad on rooftop New York Airways, circa 1977 [66] 	**Single helipad on rooftop** Embraer concept, 2018, *www.embraer.com* 
Multiple helipads on rooftop unknown operator, circa 1970 [14] 	**Multiple pad skyport on rooftop** Uber concept, 2018, *www.uber.com* 
STOL runway by a river New York Airways, circa 1969 [14] 	**STOL airpark on a barge** Georgia Tech concept, 2018 [67] 

The first row of images displays a New York Airways S-61L helicopter operating from a single helipad on the roof of the Pan Am building along with a conceptual eVTOL also on a single rooftop helipad. The S-61 could carry as many as 30 passengers and complete passenger unloading and loading on the pad in three minutes [68].

In comparison, the pictured eVTOL is capable of only supporting four passengers. Unless the turnaround time of smaller aircraft for UAM is proportionally less, the passenger throughput of a single helipad may be reduced for new UAM services compared to those of the helicopter airlines.

Interestingly, New York Airways experienced a 50% increase in revenue passenger miles in the year after opening service to this helipad on the Pan Am building [12]. This suggests the convenience of TOLAs to customer demand is a key attribute of UAM market capture.

The second row of Table 3 displays rooftop infrastructure with multiple landing pads developed to increase throughput by enabling simultaneous operations. Finally, the third row of the table displays STOL operations to a runway located on the East River, and a notional STOL airpark positioned a barge. New York Airways operated DHC-6 Twin Otters in and out of Manhattan in this manner. Reductions of ground roll through a blown-wing configuration may further increase the feasibility of siting fixed-wing airport infrastructure in dense urban areas. However, the turnaround time for Twin Otter operations was on the order of 10 minutes representing a passenger throughput reduction compared to the helicopter infrastructure [12].

Based upon the initial growth of the helicopter airlines, new aircraft, infrastructure, and ConOps were proposed to further increase system scale. Table 4 compares concepts for higher-capacity UAM infrastructure and airport integration schemes in the 1960s to current proposals.

The first and second row display how historic concepts envisioned the use of large, powered-lift aircraft operating from infrastructure located over water bodies or above highways. Compared to the rooftop facilities in Table 3, these vertiports had room to stage multiple aircraft and terminals to support customers. Current UAM concepts propose similar infrastructure, albeit for aircraft with fewer passenger seats.

The third row of Table 4 displays ConOps for UAM operations near commercial airports. These ConOps adopt a segregated strategy to develop UAM routes with vertical and/or lateral separation to conventional operations.

Chicago Helicopter Airways conducted approximately 50,000 flights per year to both Midway and O'Hare airports using a ConOps similar to that of the figure in Table 4. Furthermore, each airport opened a separate controller position for helicopter operations, assigned the helicopters to bi-directional VFR routes with 1000 ft lateral separation between fights, and authorized reduced separation between helicopters and conventional aircraft flights [69].

Helicopters today are afforded the same visibility and separation minima reductions; however, few airports current have specialized procedures or controllers to handle high-volume UAM operations.

Table 4. Comparison of 1960-era and current UAM concepts.

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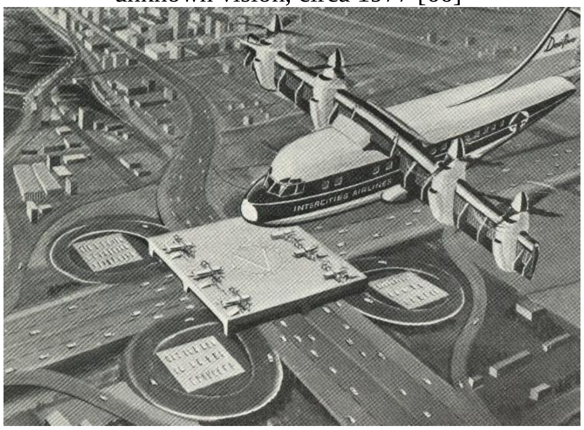
Vertiport facility over highway
unknown vision, circa 1977 [66]



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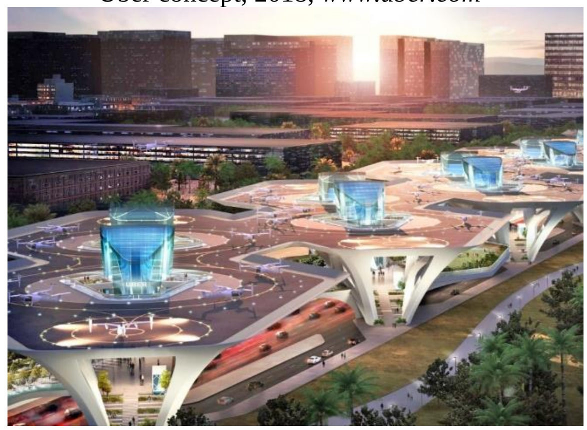
Skyport facility over highway
Uber concept, 2018, *www.uber.com*



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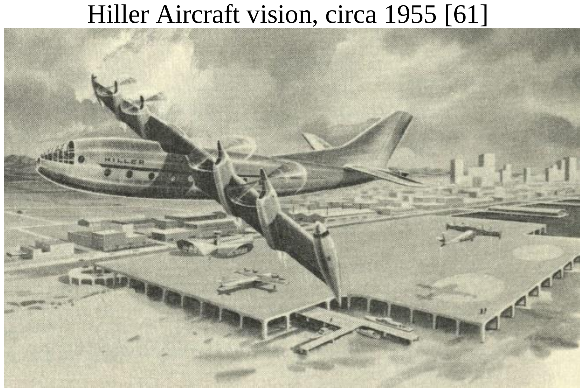
Vertiport facility over water body
Hiller Aircraft vision, circa 1955 [61]



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Skyport facility in city block
Uber concept, 2018, *www.uber.com*

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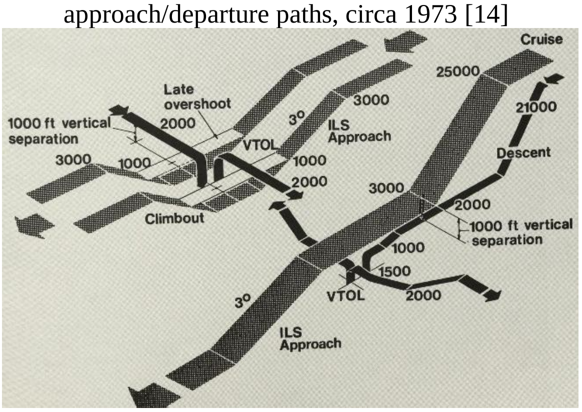
ATC ConOps for Airport Integration
approach/departure paths, circa 1973 [14]



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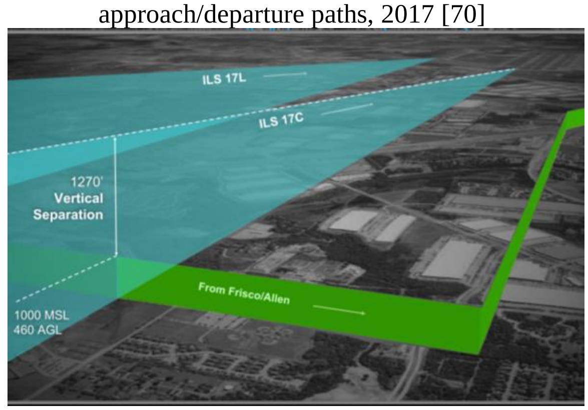
ATC ConOps for Airport Integration
approach/departure paths, 2017 [70]



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Despite the initial success of the helicopter airlines, each was ultimately forced to reduce or terminate services as a result of safety issues and economic challenges. Los Angeles Airways, which served as many as 400,000 passengers by helicopter in 1967, experienced two fatal accidents in 1968 that resulted in 44 fatalities. The accidents damaged the airline's reputation reducing customer demand and precipitating its closure in 1970 [11].

The Chicago Helicopter Airways experienced a fatal accident in 1960. While the airline had achieved between 50% and 100% growth in revenue passenger miles during each of the three prior years, passenger services diminished following the accident each year until the airway ceased commercial operations at the end of 1965. The cessation of operations coincided with the cutoff date for government subsidies which accounted for over half of the company's revenue [12].

The San Francisco and Oakland Helicopter Airlines (a single company) began operations in 1963 without the support of federal subsidies. The airline saw steady passenger growth and did not experience an accident but declared bankruptcy in 1970 due to financial difficulties despite significant airline subsidies [12]. The airline restructured and continued operations for an additional 15 years, however it did not achieve the same scale of operations as demonstrated in the 1960s.

New York Airways was the largest of the helicopter air transportation companies serving as many as half a million passengers per year in 1967. The comparative popularity of the service was achieved despite having experienced an accident with six fatalities in 1963. However, New York Airways lost market share due to rising costs during the 1973 energy crisis and unreliable access to its Manhattan heliport (the result of contract disagreements with Pan Am). The helicopter airline ultimately folded in 1979 following two additional accidents that lead to passenger and bystander fatalities. In particular, the local community permanently closed the Pan Am heliport in Manhattan and placed a ban on all non-emergency rooftop helipads precluding New York Airways access to its primary market.

Boston's Air General ceased operations in 1969 having never experienced a fatal accident. However, the helicopter charter airline did not achieve annual profitability due to low demand outside the summer months and the inclement Boston weather that reduced the reliability of the service [12].

3.2.1 Operational Issues Experienced by the Helicopter Airlines

Various concept studies in the 1970s concluded that the success of UAM systems using helicopters or other proposed VTOL aircraft was hindered by the following set of operational issues. These issues included:

- availability of TOLAs,
- scalability of air traffic control,
- community acceptance,
- safety and reputation,
- operating capabilities in inclement weather,
- high direct operating costs,
- challenging network logistics, and
- governance and policy.

The means by which each of these issues manifested in the helicopter airlines is briefly introduced in the following sections.

Availability of Takeoff and Landing Areas

Through a review of helicopter airline operations by MIT in 1970, the development of heliports in close proximity to dense urban markets was found to be one of the most impactful factors to stimulate demand for the service. In one example, the opening of the Pan Am heliport in Manhattan doubled passenger service levels for New York Airways in the following year [12].

However, the majority of helicopter airlines were limited to operating at conventional airports. Furthermore, the development of geographically distributed heliports in a region was considered to be a significant political hurdle in studies commissioned by AIAA [71] and the Los Angeles Department of Transportation [13].

Scalability of Air Traffic Control

The primary service type for the helicopter airlines was flights to and from the conventional airports connecting to mainline airline flights. The low altitude flight profile, vehicle performance, and high-frequency of flights challenged ATC at airports requiring the development of new routes, controller positions, and concepts of operation for the helicopter airlines [69]. Numerous concept studies concluded that helicopter access to airports, as well as flight in congested, uncontrolled airspace necessitated the development of an automated ATC system for airspace below 3000 ft [11,12,71].

Community Acceptance

Studies by Duke University [11,72], the RAND Corporation [72], and an AIAA committee [71] recognized noise as a potential non-technical constraint for helicopter airlines along with air pollution, effects on real estate values, and social equity. These studies did not view noise as a critical constraint at the time, and RAND proposed that helicopter noise in most locations would blend into the ambient soundscape and trigger little community annoyance. However, investigations by MIT and Los Angeles placed far greater emphasis on noise as the dominant problem facing the development of new heliport infrastructure in high-demand areas today [12,13].

Safety and Reputation

The two largest helicopter airlines were located in Los Angeles and New York and ultimately ceased operations following a series of fatal accidents that damaged their reputation, customer demand, and access to heliports in prime locations [11,12,71,72]. The safety issues of helicopters at the time resulted in public opinion and municipal policy barriers for future iterations of UAM. For example, New York City prohibited helicopter operations to rooftops after the New York Airways accident in 1977 that killed a bystander as discussed above.

Operating Capabilities in Inclement Weather

The helicopter airlines were limited to flight only under Visual Flight Rules (VFR). The inability to provide services in poor weather reduced their market demand as customers sought a more reliable transportation option. Developing the ability to provide services under Instrument Flight Rules (IFR) was therefore proposed as a critical capability to increase demand for helicopter airlines [11,12,71]. Interestingly, these studies did not highlight the increased separation minima (an ATC constraint) required for IFR operations as a follow-on scaling limitation for the helicopter airline operations.

High Direct Operating Costs

All four of the major helicopter airlines faced economic challenges due to the high operating costs of helicopters at the time. The major components of these costs were maintenance, fuel, and crew expenses [11,71,72]. Each of the helicopter airlines introduced above relied on subsidies from either the federal government or mainline airlines for a substantial proportion of their revenues.

Network Logistical Issues

Rudimentary booking, demand management, and fleet management systems available to the helicopter airlines in the 1950s through 1970s had limited capability to handle last-minute bookings or to dynamically adjust passenger and aircraft scheduling to improve efficiency. As a result, the helicopter airlines operated with average load factors of 40-50%. Furthermore, due to maintenance challenges that resulted in unplanned vehicle downtime, flight cancellations further impacted network operations. Finally, Los Angeles Airways experienced a pilot strike in 1969 that suspended all operations for a period of six months [11,12,71].

Governance

Unclear legal and regulatory jurisdictions for low altitude airspace usage led to uncertainty for where helicopter airlines could operate and what role local landowners or jurisdictions had to regulate their activities [13]. These governance issues were not resolved at the time and largely remain unaddressed today [42].

3.2.2 Relation of Helicopter Airline Operational Issues to Current-Day UAM Scaling

The operational issues experienced by the helicopter airlines are likely to impact future UAM operations as they share a similar ConOps.

Proponents of UAM suggest that emerging technologies could mitigate a number of these issues. For example, electric aircraft technologies and pilot automation may reduce direct operating costs [10] and relieve a potential shortage of available pilots. Similarly, the adoption of an on-demand or ridesharing business model similar to app-based ride hailing automobile services may lead to higher load factors, fewer deadhead trips, and improved network performance compared to scheduled or chartered flights. Improved ATC technologies and automation may enable operations in inclement weather conditions and reduce throughput restrictions in congested airspace.

However, the timeline to implement these technologies are uncertain, and furthermore their effectiveness may be offset by changes in societal expectations or the operating environment. For example, noise reductions achieved by electric aircraft compared to helicopters may not mitigate the community acceptance issue as annoyance to overflight may be triggered independently of the acoustic qualities of the sound generated by the aircraft [73]. Similarly, automation of aircraft or ATC may also exacerbate issues of acceptance from regulators, passengers, controllers, and communities.

The operational issues experienced by the helicopter airlines therefore represent a starting point from which to evaluate the scaling potential of current-day UAM operations.

3.3 VTOL Activities Since 1980

Government interest in military applications of VTOL aircraft and airline interest in sub-regional air transportation is responsible for much of the VTOL development that occurred after helicopter airline operations concluded in the 1970s. Furthermore, numerous helicopter charter and commuter networks operated during the past four decades. Both these studies and operations provide insight into potential scaling challenges and mitigation approaches for UAM.

3.3.1 Civil Tiltrotor Development and Operational Concepts

Jenkins et al. [74] reviewed a number of the urban and regional air transportation system studies conducted in the 1980s and 1990s. A core feature of developments during these years was the proposal of a civil tiltrotor (CTR) aircraft as an alternative to the helicopter that benefitted from higher cruise speeds and longer range.

Key design goals for the CTR were based upon requirements borne out of the experience of the helicopter airlines. Jenkins et al. [74] proposed that:

> *The commercial [civil tiltrotor] market requires six essential attributes: 1) vertical takeoff and landing, 2) reasonable speed (i.e., comparable to today's trip times without extra delays), 3) pressurization and customary passenger amenities, 4) acceptable safety levels, 5) high reliability, and 6) reasonable operating costs (i.e., competitive with current modes).*

Furthermore, a variety of "noneconomic customer demands" were outlined as requirements for the CTR including ride comfort (noise, vibration, space, and amenities), the ability to operate in instrument meteorological conditions and high winds, and convenient vertiport access from demand locations [74].

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Table 5 presents a number of images that display the vision of a CTR-based UAM system as proposed in the 1990s and summarized by Ref. [74]. The concepts are markedly similar to those presented two decades prior.

A few attributes to note are the increased size of the vertiport infrastructure compared to prior helicopter concepts, the use of ATC services separate from those for conventional flights, and the use of 9 to 40 passenger aircraft. The larger infrastructure and aircraft passenger capacity attributes were driven in part by a desire for increased system throughput. The vertiports displayed in Table 5 were anticipated to support on the order of 3000 passengers per day through 40 flights. The ability to operate under IFR was viewed as essential for system scaling and led to the proposal of separate terminal area IFR procedures for CTR and rotorcraft [74].

Table 5. 1990-era UAM system operations/concepts with CTR vehicle *(Ref.* [74]*)***.**

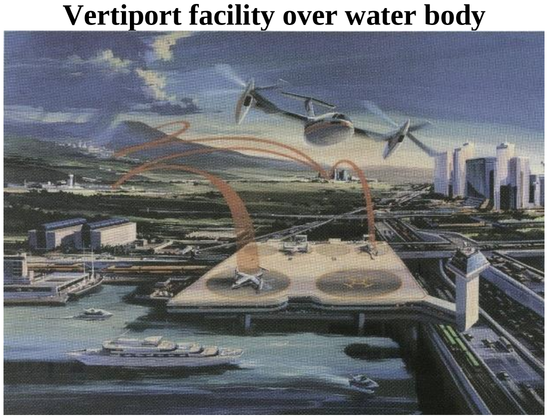
Vertiport facility over highway 	**Vertiport facility at major airport** 
Vertiport facility over water body 	**Vertiport facility over train station** 

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Fig. 5 presents major NASA technology development programs between 1987 and 2011 that sought to develop novel VTOL aircraft for commercial purposes. Concepts from 1987 to 2001 largely adopted a twin-engine, tiltrotor design similar to the Bell XV-15.

While the proposed concepts did not mature into an aircraft certified for commercial use, the technologies laid the foundation for the tiltrotor aircraft currently being considered for UAM applications. The XV-15 also supported the development of military tiltrotor aircraft development in the form of the V-22 Osprey. Furthermore, the AgustaWestland AW609 tiltrotor aircraft (passenger capacity of nine) was announced in 1996 for the CTR mission and is currently pending FAA certification. The AW609 is the closest CTR aircraft in terms of scale to current-day UAM proposals, but its 20+ year development attests to the technical and certification hurdles for aircraft of novel configuration.

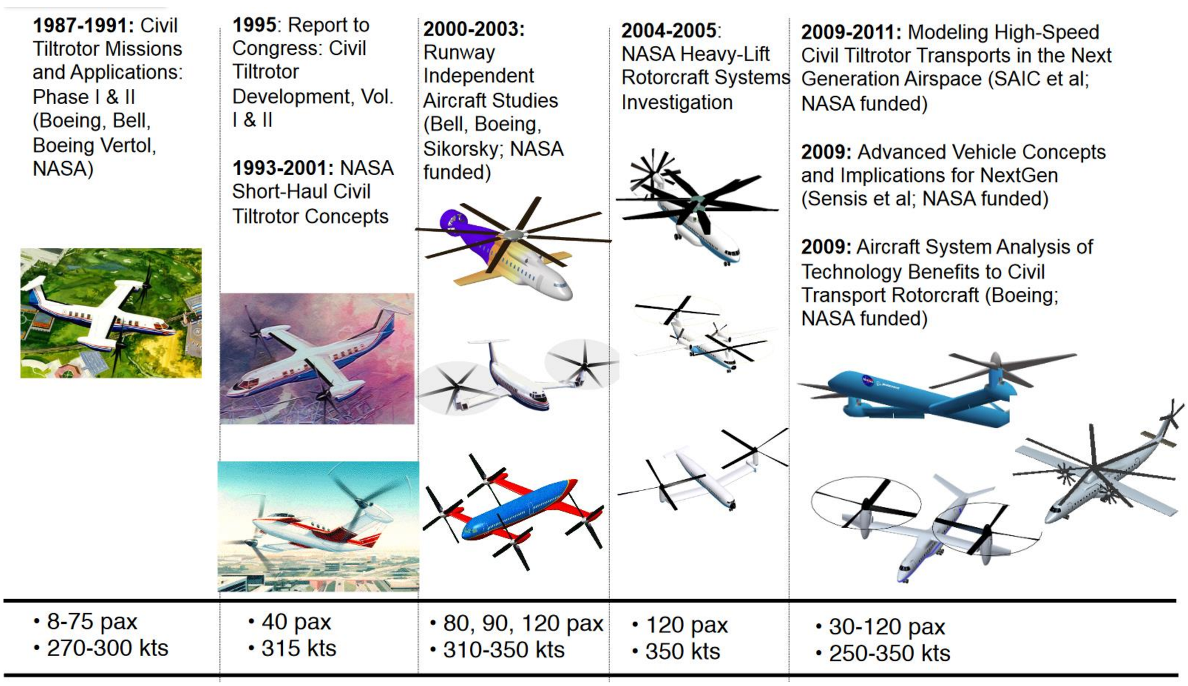

Fig. 5 NASA technology development programs for VTOL aircraft 1987-2011.
Image retrieved from the NASA Revolutionary Vertical Lift Technology Project [75].

Finally, anticipating the implementation of VTOL-capable aircraft for urban flight networks, the FAA proactively developed an advisory circular in 1991 specifically for vertiport design [76]. Although large-scale CTR operations did not materialize and the FAA cancelled the advisory circular in 2010, it serves as an important precedent for UAM operations and infrastructure development.

A variety of infrastructure was also developed and tested in this time period. For example, Dallas developed a large, elevated, public heliport in its city center that remains open today. Orlando developed a network of 60 heliports connected by special flight corridors, and Phoenix developed a similar network called the "Sun Valley" network [74]. The creation of new infrastructure was perceived as a critical scaling requirement for CTR; the policy underpinnings and heliport development during this era may benefit UAM operations today.

3.3.2 Helicopter Charter Services

While a CTR did not emerge to provide passenger services, numerous helicopter charter companies operated at various scales around the U.S. and world.

From 1986 to 1991, a helicopter commuter service called HubExpress operated in Boston providing transportation between Logan airport, a heliport in the city center, and five heliports in the surrounding communities. The average fare for the service was $109 (equivalent 2018 dollars). HubExpress operated an hourly service as an add-on ticket option in conjunction with roughly a dozen commercial airlines. The service transported over 26,000 passengers in its peak year, but like its predecessors the company folded during an economic recession in 1991.

An interesting takeaway from the HubExpress experience is that local communities challenged heliport construction and operation through zoning. HubExpress' heliport at the Hyatt Regency hotel helipad in Cambridge was closed by the city council shortly after opening due to noise and safety complaints by local residents [77].

In an international example, Atlas Helicopter began operations in 2001 in London and continues to this this day. The company primarily provides charter services, but for a brief period beginning in 2008 experimented with operating regularly scheduled flights into London from a variety of locations in the South of England.[4] Unlike HubExpress which benefited from low-cost access to helipads built by clients on private property, Atlas experienced high-cost landing fees at the London heliports. The general manager of Atlas shared in 2015 that their typical landing fee at Battersea Heliport in London ranged from $1015 (equivalent 2018 dollars with a July 2018 pound-dollar exchange rate) to $1993 for a single Augusta 109 aircraft (a maximum of six passengers).[5]

Furthermore, Atlas' operations to Battersea Heliport have also been threatened by community acceptance related to perceived safety and noise of helicopter flights. The issue came to a head with the election of London mayor Sadiq Khan in 2016 when his administration stated that "new heliports should be refused, other than for emergency services, and steps should be taken to reduce helicopters overflying London" [78]. The experience of Atlas reinforces the criticality of ground infrastructure and community acceptance as scaling constraints for UAM.

As a third example, Liberty Helicopters in New York began business charter operations in 1986 and expanded to sightseeing in 1990. The company has grown to be the largest helicopter sightseeing and charter service in the New York metropolitan area. However, during its 30 years of operation it has had five accidents, two of which had fatalities. Similar to HubExpress and Atlas, Liberty Helicopters experienced significant scaling challenges as a result of community acceptance of noise and safety. In 2017 the New York City Council reduced the number of helicopter tours in New York by 30,000 annual flights and capped the services at 50% of its prior market [63]. Liberty Helicopters is also facing public resistance to its operations to the Hamptons based on noise complaints from local residents.

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[4] https://www.shephardmedia.com/news/rotorhub/atlas-helicopters-to-offer-timetabled-he/
[5] https://www.virgin.com/travel/helicopter-commuter-transport-future

3.4 Small Aircraft Transportation System and Commuter Airlines

3.4.1 Small Aircraft Transportation System

In parallel to the development of CTR aircraft and operations, NASA pursued the development of a small aircraft transportation system (SATS) from 2000 to 2005 that sought "to enable people and goods to have the convenience of on-demand, point-to-point travel, anywhere, anytime for both personal and business travel" [79]. The concept anticipated the use of four to nine passenger propeller or jet aircraft operating between regional, reliever, and general aviation airports or heliports. Two new classes of aircraft were anticipated to operate under the SATS concept: very light jets (VLJs) and personal air vehicles (PAVs) [16,80].

The premise of SATS was that there was an extensive network of existing aviation infrastructure that was generally underutilized and at which flight operations were acceptable to the public. Furthermore, the distribution of this infrastructure was considered sufficient to capture substantial inter-city market demand (albeit not intra-city UAM markets) [81,82]. Viewing infrastructure as not a critical constraint for system scale, the SATS program focused on technology development to address other scaling constraints identified in the helicopter airline and CTR experience, namely air traffic control, weather-tolerant operations, and network logistics.

Air Traffic Control

A core focus of the SATS program was to develop the capability for small aircraft to operate at high flight densities under IFR or VFR to and from non-towered airports. While busy airports had dedicated separate controllers to manage high-volume helicopter airline operations, it was not perceived as economically viable to provide ATC services to the 3400 small community airports the SATS program anticipated using.

Current ATC policies restrict IFR operations at non-towered airports to a one-in/one-out scheme. This policy results in low throughput capacity for the facility as only one IFR operations may be on approach, departure, or a taxiway at a time.

To address this constraint, the SATS program developed a new type of terminal airspace for small airports called a self controlled area (SCA) in which an automated ATC system enabled pilots to take responsibility for their own separation and sequencing using information provided by the automated system. An SCA was defined around a non-towered airport that required special training and aircraft equipage to enter, but relieved conventional controllers of flight service responsibilities [83].

Furthermore, the SATS program also sought to address controller workload capacity limits outside the SCAs by developing new en-route procedures to manage SATS aircraft interaction with controllers. This technology metered SATS aircraft exiting the SCA into a specific controller's sector to manage workload and defined separate en-route procedures for SATS flights [79].

The central takeaway from the SATS developments in ATC is that controller workload was perceived as the primary scale-limiting attribute of the current ATC system. The SATS approach to mitigate this constraint was to segregate UAM operations and enable pilot self-separation assisted by automation.

Weather-Tolerant Operations

The SATS program proposed that reliably providing UAM operations in nearly any weather condition was necessary to capture consumer demand and facilitate the scaling of a UAM system. However, 80% of the small airports they intended to use did not have precision approach and landing guidance, and single pilot IFR operations were limited. NASA therefore developed a suite of airborne technologies to support single pilot IFR operations. These developments included advanced flight displays and flight directors, enhanced vision, and heads up displays. When implemented together, the SATS program anticipated supporting lower landing minimums at non-towered airports and reduced pilot workload [79].

Network Logistics

All four of the helicopter airlines faced economic challenges in the 1960s and 1970s. One research focus of the SATS program was to leverage operations research capabilities and computational resources to manage the UAM networks to increase average aircraft load factors and unit profitability. DayJet Corporation, a commercial SATS operator, worked on the development of a multicommodity network flow model for the "dial-a-flight" problem in order to enhance vehicle, passenger, and pilot load balancing of their network [80].

3.4.2 Commuter Airlines

Although commercial SATS operators were unable to reach economic viability and ceased operations following the 2008 financial crises, a variety of commuter airlines have thrived in the United States.

Commuter airlines provide short distance, inter-city flights where demand is either too small for mainline service or distances are too short to justify the use of large aircraft. These airlines typically operate with a Part 135 operating certification using aircraft with a capacity of nine passengers or less and, in some cases, single pilots. Commuter airline routes are frequently either subsidized by the government (such as the U.S. Essential Air Services or the Norwegian Public Service Obligation programs) or are higher-cost than commercial flights of comparable length.

As one of the largest commuter airlines, Cape Air is representative of inter-city UAM and has been operating since 1989. Cape Air's viability has been maintained by mitigating a number of the constraints that hindered the previous UAM systems.

First, 98% of Cape Air's non-government subsidized routes have a range of 100 miles or less, and 46% of this subset of routes are 50 miles or less [84]. Despite operating on these short ranges, Cape Air does *not* use VTOL aircraft and relies upon fixed-wing services at general aviation, reliever, and major airports. The airline specializes in short-distance routes where travel on the surface is particularly slow due to congestion, water bodies, or a lack of infrastructure.

However, as a result of exclusively using existing infrastructure, Cape Air has faced cost, convenience, and throughput constraints due to congestion (both in the terminal and on the airfield) at large airports and the long first-mile/last-mile transportation to these airports. The airline is now attempting to begin seaplane flights between the Boston harbor and New York's Hudson River to address these challenges. The water bodies in these cities are anticipated to serve as TOLAs in close proximity to the airline's customers.

Cape Air also operates with a single pilot in all weather conditions. The airline has not been subject to notable community acceptance concerns, perhaps due to operating from existing airports or the lower noise of fixed-wing aircraft compared to helicopters. From a network management standpoint, Cape Air operates scheduled flights with pre-published departure times. On some routes during high demand periods Cape Air may schedule flights as often as every fifteen minutes.

A second commuter airline of note is Kenmore Air located in Seattle. Similar to Cape Air, Kenmore Air has found a market niche providing sub-regional flights on routes where surface transportation is slow or not possible. The airline also exclusively operates fixed-wing aircraft and operates from existing airport infrastructure and a number of water bodies.

3.5 Emerging Urban Air Mobility Operations

In the past decade a number of transportation network companies (TNCs) have emerged that offer private or ride-sharing helicopter charter operations.

For example, both Airbus and Uber began operating smartphone based aerial ride hailing services in São Paulo in the past five years. Although operating at a loss, these two services represent the first experiments with adapting new telecommunications technologies and business models to urban flight networks. Their experiences provide a proof of concept for the benefits and limitations of new technologies to overcome the financial and logistics challenges experienced by prior UAM operators. Furthermore, their helicopter network in São Paulo is breaking new ground in terms of the scale of its infrastructure and operations. Some sources report that there are now over 400 helicopters traveling between a network of more than 250 helipads in the city [85].

Another helicopter TNC, Blade Urban Air Mobility, Inc., operates in New York where it coordinates local charter companies to provide flights between Manhattan, the Hamptons, and the three major airports. Blade has partnered with various surface transportation modes (bus, boat, app ride) to provide intermodal, door-to-door transportation services in order to reduce first-mile/last mile travel time. It also limits surface travel by operating from a set of heliports located on Manhattan's periphery in close proximity to their client base.[6]

Each of the three UAM helicopter networks discussed above have also experienced operational challenges similar to those introduced in this chapter. Airbus has stated that one of their most pressing challenges in São Paulo is ATC and the ability to operate numerous flights in an airspace, especially under IFR. Up until April 2018, helicopter operators in São Paulo were limited to six simultaneous flights in a significant volume of airspace over the city; this was likely due to ATC controller workload limitations [86]. An updated operational policy following April 2018 no longer sets a fixed numerical limit on the number of helicopters controllers may support.

While Airbus and Uber have not faced notable community acceptance challenges in São Paulo, Blade received repeated community noise complaints and legal challenges to its operations in the Hamptons. Differences in community acceptance between the two cities are not the result of differences in noise emissions as all three services use similar helicopters and ConOps, but rather the result of differing community sensitivities to noise and their ability to act against the operator.

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[6] Blade: https://blade.flyblade.com/

In addition to these emerging operators, beginning in 2010 NASA presented a vision for an "On-Demand Mobility" (ODM) system that relied upon small, electric aircraft and autonomy to conduct UAM operations in proximity to a metropolitan area [23].

NASA led a series of roadmapping workshops on ODM in 2015 and 2016 in collaboration with the FAA [87]. These workshops brought together regulators, operators, manufacturers, and academics interested in UAM concepts to produce roadmaps for key areas of development to achieve scalable UAM operations. The roadmaps concerned [88]:

- vehicle operations (flight and trajectory control, avionics, perception, and planning),
- airspace integration and air traffic control,
- electric propulsion,
- community acceptance,
- manufacturing, and
- aircraft structures and materials.

Simultaneously, NASA leveraged electric aircraft technologies and ATC developments from the previous PAV and SATS programs to support research that addressed operational [8,19,28], certification [21], and economic challenges [9,10,27] of UAM. In particular, a 2016 concept study in the Silicon Valley provided a first-pass evaluation of UAM operations and network scaling [31]. This study suggested that community acceptance of noise was the most severe design constraint for UAM, followed by airspace management and capacity, infrastructure development, and direct operating costs.

Beyond NASA, Uber Technologies Inc. released a white paper in 2016 which outlined their concept for UAM using all-electric VTOL aircraft to provide intra-city and airport shuttle services [5]. The white paper proposed infrastructure development as the most significant scaling constraint for UAM. Pilot training/automation, certification, aircraft noise, aircraft charging, weather, air traffic control, emissions, and economics were also cast as potential scaling constraints. Concurrent studies by NASA and the author provided additional detail into these potential constraints [31,44].

Finally, over a dozen aircraft manufacturers tested full-scale prototype VTOL and/or STOL aircraft for UAM by the end of 2019. These manufacturers anticipate entry into service of a certified aircraft by the mid-2020s. These new aircraft, which are generally one to four passenger vehicles with distributed electric propulsion, may augment or replace the helicopter and bring to bear new capabilities, as well as new limitations, for UAM operations. In addition to these prototype aircraft, the Vertical Flight Society is also tracking over 200 additional aircraft concepts that have been announced for UAM.[7]

[7] Electric VTOL News by the Vertical Flight Society, evtol.news, accessed 10/30/2019.

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4 Identification of Potential Scaling Constraints

This chapter identifies an initial set of constraints that may impact the ability of a UAM system to increase the scale of its operations. The anticipated impact of each constraint on UAM scaling is discussed, and two constraints are selected for further investigation.

4.1 Approach

Potential scaling constraints were identified through exploratory case studies of UAM operations in three metropolitan areas with diverse operating environments. Los Angeles was selected as a city case due to an expectation that it was uniquely suited as an early adopter of UAM because of its large consumer base, severe surface congestion, extensive helipad and airport infrastructure, and generally benign weather. Boston and Dallas were selected as additional city cases in order to evaluate UAM operations in regions with different geographic structure, demand patterns, and weather. Based upon the experiences of historic helicopter airlines and charter services, it was anticipated that different scaling constraints for UAM would result in response to the different attributes of the three cities.

The first step of each case study was to identify origin and destination locations of consumer demand for each of the three UAM service types presented in Fig. 3 (namely intra-urban services, airport shuttle services, and inter-urban services). This was accomplished through the use of census data to estimate commuter travel patterns (routes, times of day, number of individuals, etc.) and the identification of special attractors in each city case including airports, financial districts, sports arenas, and hospitals.

Second, between 10 and 12 representative “reference missions” were defined per city case to represent diverse operational characteristics for the UAM services. Third, a “day in the life” evaluation of the UAM ConOps presented in Section 2.2 was conducted for each reference mission. Operational challenges that may inhibit or delay the completion of the mission were recorded.

Fourth, the set of operational challenges from the reference missions was condensed into a set of potential scaling constraints for UAM. The impact of each constraint on the feasible scale of UAM operations was considered with support from the case studies or additional analyses. The identified constraints were also compared to those experienced by historic helicopter airline services discussed in Chapter 3.

4.2 Exploratory Case Studies of UAM Operations

A summary of the exploratory case study analysis is provided below. Greater detail on the case studies may be found in Ref. [40].

4.2.1 Identification of Origin and Destination Locations for Customer Demand

Fig. 6 presents the geographic boundary for each city case study plotted overtop of a population density map. The boundaries were defined to include the major population centers within approximily 50 NM of the primary downtown area and census tracts with at least 101 people per square mile. The Los Angeles case study boundary was elongated to include San Diego which was anticipated as a likely inter-urban market for UAM.

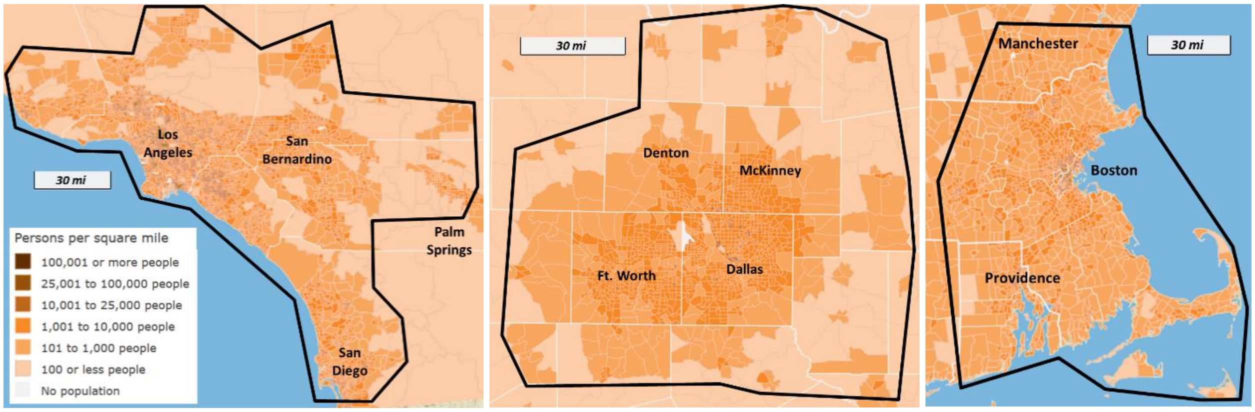


Fig. 6 Los Angeles, Dallas, and Boston city case boundaries.
"USA Population Density" map data © 2013 Esri, retrieved from www.arcgis.com.

Within these boundaries, potential demand for UAM services was modeled in order to define origin and destination (O-D) locations for the reference missions. The following resources were used to model potential demand for the three UAM service types introduced in Fig. 3:

1) The U.S. Census Bureau's American Community Survey (ACS) 2014 Longitudinal Employer-Household Dynamics O-D Employment Statistics (LODES) was used to identify census tracts where residents experience long-distance commutes. These census tracts represent potential demand locations for intra-urban UAM services as the service may offer large time savings to commuters.

2) Consumer wealth data, estimated by home valuation and average household income, was collected to identify high income or wealthy communities. Wealthier communities were anticipated to have a higher willingness to pay for UAM services and represent potential demand locations for the intra-urban or airport shuttle services.

3) Current helicopter charter and commuter airline services were reviewed to identify existing demand for inter-city air transportation and the routes which they operate.

4) Demand "special attractors," including public event venues with capacities greater than 15,000 people, city centers, transportation hubs (public airports, train stations, and subway stations), notable tourist areas, and hospitals with more than 100 beds, were identified in each city case. The special attractors represented potential O-D locations for all three UAM service types.

Through the LODES census data, "commuter communities" were identified in each of the three city cases. A commuter community was considered to be a census track from which a minimum number of individuals traveled from to their place of employment. The minimum number of commuters required to define the community was 2000 individuals for Dallas, 4000 individuals for Boston, and 10,000 individuals for Los Angeles.

As an example of this process, Fig. 7 presents a laborshed heat map of the number of commuters who travel from outlying communities to within three miles of the Fort Worth or Dallas city centers for work. It should be noted that the development of a viable UAM system may "induce" new demand and increase the number of long-distance commuters; this type of demand was not considered in these case studies.

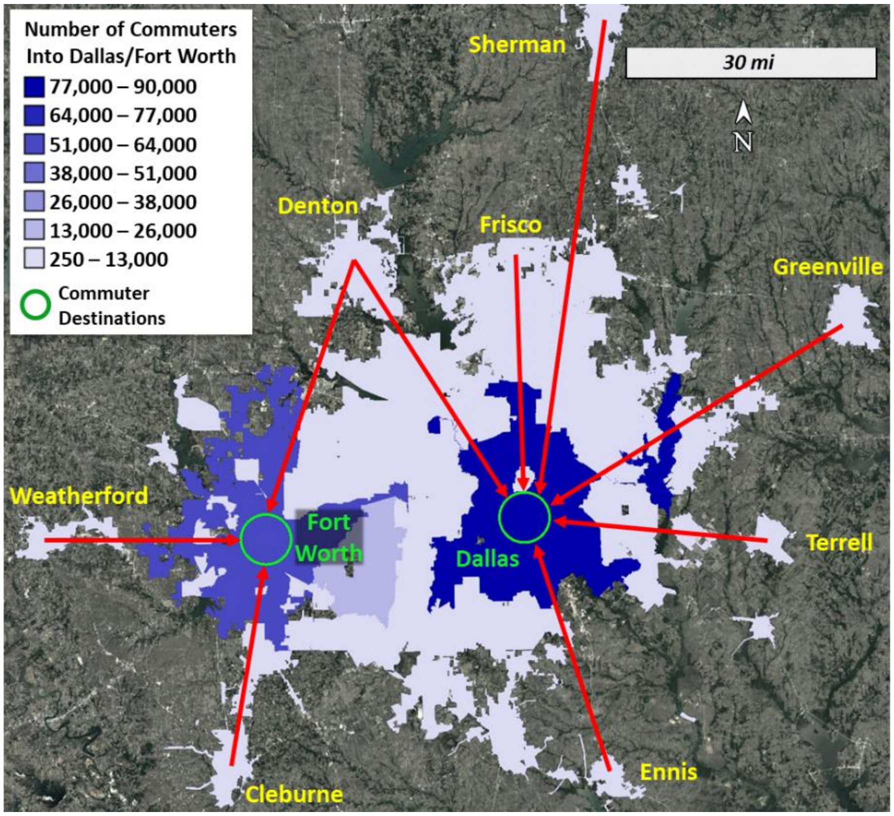


Fig. 7 Heat map of commuter flows from outlying communities into Dallas-Fort Worth.
© 2017 Google, Map Data: Landsat/Copernicus. Travel Data: U.S. Census Bureau OnTheMap

"High-income communities" were characterized either as census block groups with average household income of at least $200,000 or as neighborhoods with average home valuations of greater than a threshold value chosen for each city. A valuation threshold of one million dollars was used for Los Angeles and Dallas, while a threshold of $900,000 was used for Boston to capture differences in their housing markets.

The demand special attractors (event venues, transit hubs, hospitals, etc.), high-income communities, and commuter communities form the set of potential locations (O-D pairs) from which the UAM reference missions were defined.

4.2.2 Definition of Reference Missions

Representative UAM reference missions were developed for each city case by selecting pairs of O-D locations from those defined in the previous section. A pair of O-D pairs was selected to define a route through four different approaches.

1. O-D locations that were closest to current helicopter or small aircraft charter routes were selected to define four reference missions. These reference missions tended to be longer range, inter-city trips or trips from a city center to an outlying special attractor such as a winery or tourist location.

2. Origin locations representing commuting trips from either the commuter or high-income communities were used to define 11 reference missions. Census data was used to identify

census tracts where a large number of commuters travel to from each origin point in order to select realistic destination locations for these reference missions. An example of this process is displayed in Fig. 8 for a reference mission from the commuter community of Hull to the Boston financial district.

An "inverse" laborshed mapping was developed for Hull as presented in Fig. 8. Darker blue regions of Fig. 8 represent census tracts where more residents from Hull traveled to for work to each day. While the largest number of commuters remained within Hull for their primary employment, another large group of workers (329 individuals or 9% of all workers according to the LODES data) traveled to the financial district of Boston. The financial district was therefore selected as the destination point for the reference mission.

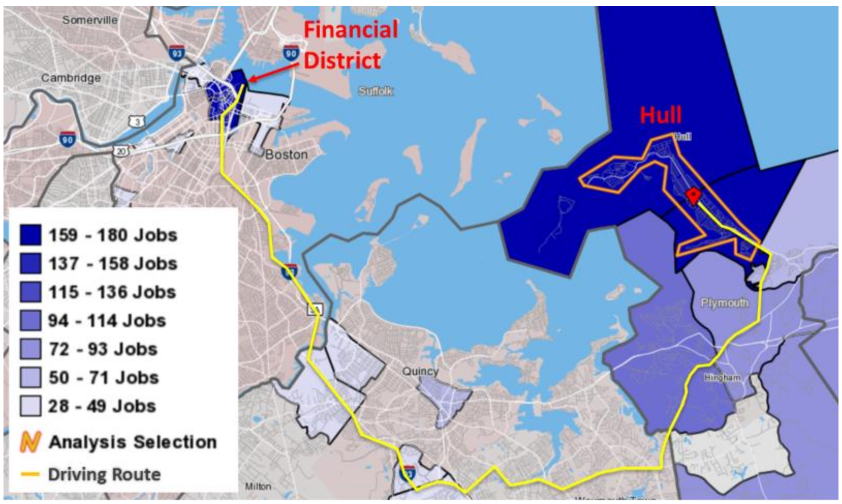


Fig. 8 Hull community (Boston) inverse laborshed map.
Image developed with the U.S. Census Bureau OnTheMap application. http://onthemap.ces.census.gov/.

3. An additional 10 reference missions were defined by selecting either one or both the origin and destination points from the set of special attractors identified in each city. If only one special attractor was used in the mission, then the other end of the mission was either a commuter or high-income community.

4. Lastly, O-D locations were randomly generated within the city case boundary presented in Fig. 6 to create seven reference missions. It was anticipated that randomly defined missions may address potential selection bias inherent to the missions defined from current-day travel patterns and demand. Trips of less than five miles were re-generated.

Except for the randomly selected O-D points, an additional objective of O-D selection was to create reference missions that exhibited diversity in the following attributes; it was anticipated this diversity may lead to the identification of different scaling constraints.

- Mission Length – the haversine distance between the origin and destination.
- Airspace Interaction – the number and type of controlled or special use airspace that the UAM aircraft may interact with during its mission.

- TOLA Availability – the proximity of the origin and destination locations to an existing airport or heliport.
- Surface Route Diversion – the ratio of the surface route distance to the haversine distance between the origin and destination. Larger surface route diversions may increase the time savings of a UAM alternative.
- Surface Congestion – the ratio of the peak congestion to free flow surface travel time. Worse congestion may increase the time savings of a UAM alternative, but also slow first-mile/last-mile travel to/from TOLAs. Fig. 121 in Appendix E provides an example and description of the approach used to estimate surface congestion.
- Population Overflight – The population density of the areas between the origin and destination that may be overflown during the UAM mission.

In total, 32 reference missions were defined. Figures of each city's reference missions and a table of their attributes may be found in Appendix E. Because the reference missions were selected to demonstrate diverse attributes, they were not intended to represent the largest market opportunities for UAM or missions with the lowest barriers to entry in each city. The reference missions should therefore not be considered as proposed initial services for UAM.

4.2.3 Evaluation of Operational Challenges for the Reference Missions

Fig. 4 introduced a generic ConOps for a UAM mission that defined the set of activities completed from the time the customer ordered the service to shortly after the customer reached their destination. These activities included customer ground transportation, flight crew and aircraft dispatch and repositioning, the customer's flight, and arrival or diversion to an alternative TOLA.

A step-by-step evaluation of the ConOps was conducted for each reference mission to identify potential operational challenges. An operational challenge was considered to be a factor that could limit or prohibit throughput of UAM operations on a specified route.

For example, if a UAM aircraft required entry into a controlled airspace to access a TOLA, then a verbal exchange with the air traffic controller and the controller's workload level could delay or prevent the operation; this would be noted for that mission as a potential operational challenge. A walk through of each step of the UAM ConOps with examples of how the operational challenges manifested in these reference missions is provided in Ref. [40].

Nineteen potential UAM operational challenges were identified through the evaluation of the reference missions. These challenges were grouped into three types:

1. Systematic – challenges that were anticipated to impact UAM flights on all reference missions independent of the attributes of the mission or the number of flights occurring on the route (i.e., the scale of operations).
2. Scale-dependent – challenges that were anticipated to become more restrictive to UAM flights as the number of flights occurring on the reference mission route increased.
3. Mission-specific – challenges which were anticipated to restrict the number of flights occurring on the reference mission route due to a specific attribute of the operation (e.g., weather, length, or special use airspace).

The identified challenges are presented in Table 6 where they are grouped by the mission ConOps step in which they manifested. While the flight segment of the UAM ConOps resulted in the plurality of operational challenges, a number of challenges concerned non-flight activities, including customer first-mile/last-mile transportation, aircraft surface activities, and network management.

Table 6 Potential UAM operational challenges identified from reference missions

Mission ConOps Step(s)	Identified Operational Challenge
Aircraft pre-flight	1. Current and/or predicted weather restrictions 2. Pilot staffing 3. Aircraft staging between flights 4. Dispatch and reserve regulations for minimum fuel/energy
First-mile/last-mile surface travel to/from TOLA	5. Proximity of TOLAs to customer origin and destination 6. TOLA integration with ground transportation networks
Customer activities at the TOLA	7. Customer physical access to TOLA 8. TOLA and aircraft security
Flight segment	9. Access to controlled airspace 10. Pilot communication with ATC 11. Safety in high density flight areas (including interactions with UAS) 12. Community acceptance of flight operations 13. Approach and departure clearways at TOLAs 14. Required VTOL or STOL capability 15. Throughput capacity of TOLA 16. Availability and prioritization of alternate TOLA
Aircraft transition to the next operation	17. Aircraft fueling or charging duration 18. TOLA fueling or charging infrastructure 19. Geographic balance of aircraft and pilots with customer demand

Three of the operational challenges presented in Table 6 were systemic in nature. These challenges included the development of minimum dispatch and reserve “energy” requirements for electric or hybrid-electric aircraft, the provision of security services and passenger screening at TOLAs, and the development of hydrocarbon or electrical fueling/charging infrastructure at TOLAs.

Four of the challenges were perceived to be dependent upon the scale of operations. For example, the throughput capacity of a TOLA directly influences the number of flights that may be conducted on a reference mission. Staging capacity, aircraft refueling/charging duration, and the pilot staffing were also operatorial challenges that depended upon the scale of operations. These challenges were likely to be present in any reference mission for high-volume operations.

The other 12 operational challenges were mission-specific and only present in some of the 32 reference missions based upon the attributes of the mission. Fig. 9 maps these mission-specific operational challenges to the reference missions in which they were identified. Table 45 in Appendix E presents the metrics used to determine if the challenges existed in each reference mission.

Fig. 9 Variation of mission-specific operational challenges in the 32 reference missions.

A few key trends were apparent from the mapping in Fig. 9. First, columns five and six display that only two of the 32 reference missions did not require access to surface-level controlled airspace. Interacting with ATC and gaining access to controlled airspace was therefore anticipated to be critical for UAM systems and may constitute a significant scaling challenge.

Twelve of reference missions, including nearly all in Boston, did not have an existing TOLA located in close proximity to the mission's origin or destination (column 2). Furthermore, for the 20 missions where there was existing infrastructure in close proximity, only four of these missions could use public-use airports near both the origin and destination. The remainder of the missions utilized existing heliport infrastructure which would require STOL or VTOL aircraft capabilities (column 10). These helipads were generally located on private properties or rooftops that were not certified for public operations; customers may therefore by unable to access these facilities (column 4). Considering these limitations, existing aviation infrastructure was not well-suited to support high-volume UAM operations in any of the three cities except on a few routes.

Inclement weather conditions that may reduce UAM system performance were more frequent in Boston (column 1) where Instrument Meteorological Conditions (IMC) would require IFR UAM operations more than 10% of the year; winds over 15 kts were also reported 11% of the year in Boston. In comparison, Dallas and Los Angeles reported IMC 5% and 7% of the year respectively, and winds over 15 kts 11% and 2% of the year, respectively. Dallas also was the only city with significant convective action which was present 6% of the year.

A majority of the reference missions in all three city cases utilized published helicopter or VFR corridors where they were more likely to interact with other air traffic (column 7). However, because the reference missions in this study leveraged existing heliport and airport infrastructure, all but four of the approach and departure clearways used by the reference missions were free of obstructions or interaction with other airport procedures (column 9).

4.2.4 Potential UAM Scaling Constraints

The 19 challenges presented in Table 6 were a first-pass effort at identifying what aspects of UAM operations and its ecosystem could limit the scaling of the service. As such, many of the challenges concern similar features of UAM operations (e.g., TOLA throughput capacity and staging capacity) or are likely to influence UAM scaling with different levels of severity (e.g., customer physical access to TOLAs vs. flight access to controlled airspace).

To refine the analysis, the operational challenges were condensed into seven potential scaling constraints for UAM. These constraints were TOLA availability, ATC services, community acceptance of UAM operations, safety and certification of UAM aircraft and operations, pilot availability, the logistics of UAM network operations, and weather restrictions to UAM flight.

Fig. 10 displays how each of the challenges identified in the case studies contributed to the definition of each constraint. The number of operational challenges that contribute to any one constraint does not indicate that specific constraint is of greater severity than any other, but rather it suggests that there may be more mechanisms through which the constraint could impact UAM operations and scaling.

The following section discusses each constraint and its potential impact(s) on UAM scaling.

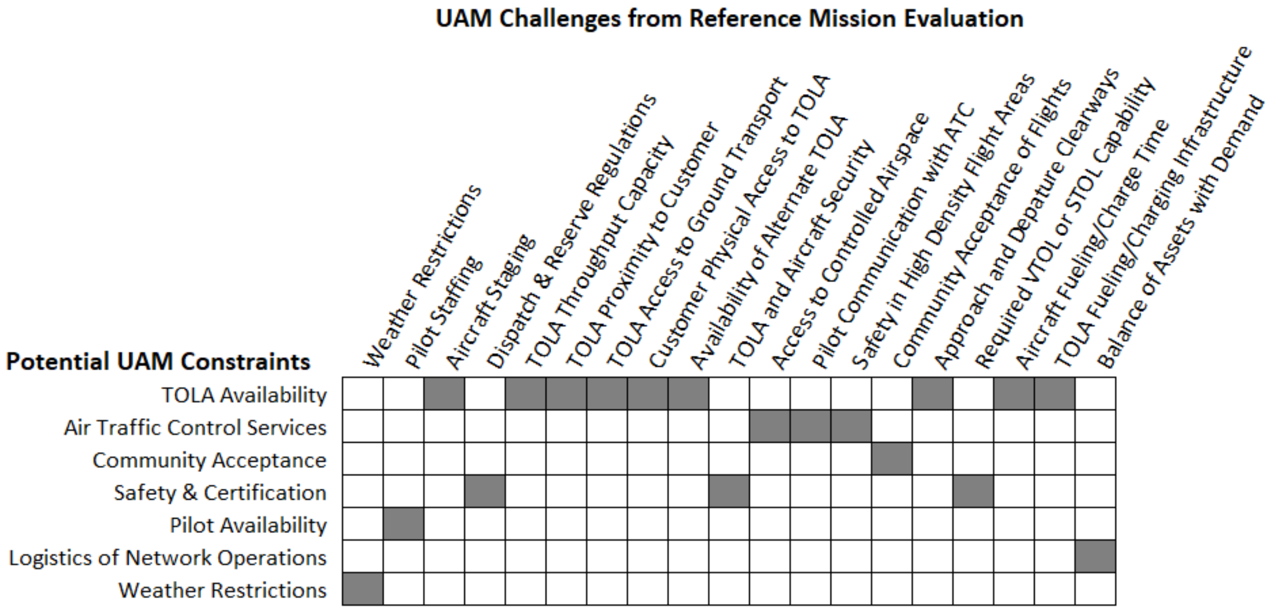


Fig. 10 UAM operational challenge to constraint mapping.

4.3 Discussion of Potential Scaling Constraints

The seven potential scaling constraints identified for UAM are discussed below based upon the findings of the exploratory case studies. Further detail on the constraints from relevant literature is provided. The influence of each constraint on UAM scaling is introduced.

4.3.1 Takeoff and Landing Area (TOLA) Availability

Nine of the 19 operational challenges identified in the reference missions concerned attributes of TOLA infrastructure. Considered jointly, these challenges point to two key requirements for TOLAs to support the scaling of a UAM network, namely:

1. TOLAs must be conveniently accessible to customers, and
2. TOLAs must provide sufficient passenger and aircraft throughput to support scaling.

Accessibility refers to the ability of customers to rapidly reach the departure TOLA from their trip origin point and then to rapidly reach their destination point from the arrival TOLA. Unlike commercial airlines for which an hour or longer trip to the airport typically represents a small fraction of the alternative mode's trip time, UAM flights may not provide sufficient time savings en-route to tolerate long first-mile and last-mile connections.

Network simulations by Purdue University [89], RWTH Aachen University [37], and Uber Technologies Inc. [5] have each shown that reducing first-mile and last-mile travel time strongly influence the ability of UAM to attract customers and increase the scale of the service from a demand perspective. The accessibility of TOLAs may be increased by siting the facilities closer to demand or by reducing the travel time to the facilities through intermodal connections to transit and the road network. Researchers at Georgia Tech have evaluated where TOLAs may be sited for UAM and found that reducing the footprint of the facilities most strongly increases their ability to be located in proximity to demand [67,90,91].

While TOLA accessibility primarily affects scaling from a demand perspective, the throughput capacity of TOLAs influences scaling from a UAM supply standpoint. TOLAs act as the entry and exit nodes for passengers in the UAM flight network. Therefore, TOLA throughput directly influences the feasible scale of operations. Passenger throughput is a function of the rate at which passengers may be processed in the terminal (check-in, security screening, etc.), the aircraft throughput of the airfield, and the passenger capacity of each aircraft.

Of these three components of passenger throughput, terminal capacity has typically not constrained aviation operations. Aircraft throughput depends upon aircraft performance (e.g., runway occupancy time and gate turnaround time), ATC attributes (e.g., inter-arrival spacing), and TOLA design attributes (e.g., number of gates and runways/landing pads). The passenger capacity of UAM aircraft is related to the footprint of TOLA infrastructure, the type of operating certificate desired from the FAA, and/or the technical or economic constraints of aircraft design. Additional research is necessary to characterize how these attributes influence feasible TOLA throughput; this is the focus of Chapter 5.

Existing aviation infrastructure did not simultaneously provide convenient access and high-throughput for the UAM missions in the case studies. While airports had the potential for large throughput capacities, they were typically located outside densely populated areas and required extensive first-mile or last-mile travel to access. Heliports, while often located within urban areas, typically had low throughput capacity, were generally not accessible to the public (e.g., were on private buildings), and most were not approved for commercial operations. These characteristics were expected to be representative of most cities beyond those considered in the case studies.

Fig. 11 presents the type and location of the existing aviation infrastructure within the case study cities. Table 7 displays the corresponding number of facilities by type in the cities. Although all three cities appeared to contain a substantial number of TOLAs, the geographic distribution and throughput capacity of these facilities was ill-suited to serve a majority of the reference missions. Over 80 of Los Angeles' helipads were located within two miles of the city center, and over 70% of these facilities were for emergency use only. Boston supported only medical heliports within its city center. Dallas was the only city with a high-capacity, public facility in its city center.

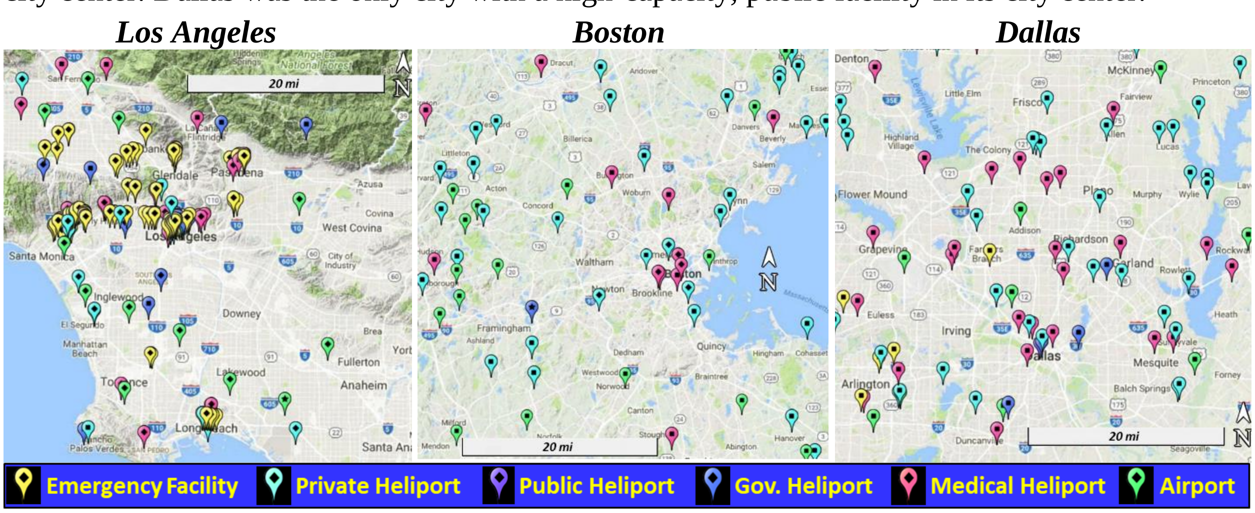


Fig. 11 Existing heliport and airport infrastructure in the Los Angeles, Boston, and Dallas case studies. *Map Data © 2017 Google.*

Table 7 Existing TOLAs by type in Los Angeles, Boston, and Dallas case studies

TOLA Type	Los Angeles	Boston	Dallas
Emergency Helicopter Landing Facility	218	0	1
Private Heliport	37	95	78
Government Heliport	15	3	3
Medical Heliport	24	41	53
Public Use Heliport	0	0	4
Airport	96	84	174
Total Existing Aviation TOLAs	390	223	313

Furthermore, 50% of the reference missions did not have the ability to stage five or more aircraft at a facility within five miles of the pickup TOLA. A lack of staging reduces TOLA throughput capacity as shown in Chapter 5. Finally, 56% percent of the reference missions operated to or from TOLAs that could only support a single aircraft at a time.

Without sufficient existing TOLA infrastructure, the scaling of UAM operations necessitates the development of new facilities and/or the retrofitting of existing infrastructure. However, previous UAM operators, including the helicopter airlines, experienced difficulty developing or operating from TOLAs in urban areas due to community acceptance concerns about noise and safety as discussed in Chapter 3. More information on how community acceptance influences TOLA availability is provided in the following section.

Finally, TOLA infrastructure co-located with large commercial airports presents unique challenges for UAM scaling. Airport facilities are less footprint restricted and have higher ambient noise levels to mask UAM noise emissions. However, TOLA operations at airports are more sensitive to ATC constraints and interactions with large aircraft. Chapter 8 evaluates TOLA siting and operations near airports in greater detail.

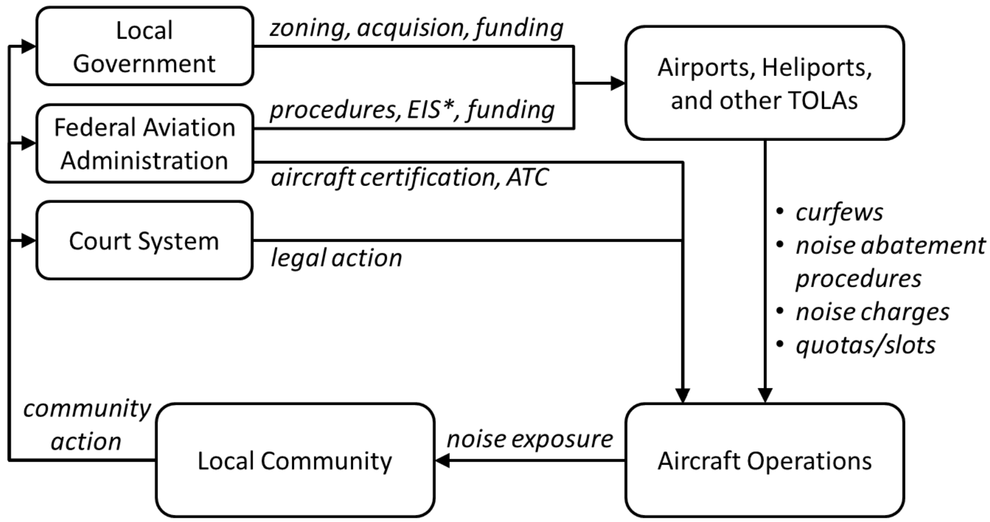
4.3.2 Community Acceptance

Although community acceptance of UAM may be influenced by numerous factors including privacy, viewshed, pollution, safety, and equity, aircraft noise has been the most common aviation externality leading to community-imposed limits on the scale of prior helicopter and transport aircraft flights.

For example, airports in Phoenix, Charlotte, Boston, and Los Angeles experienced significant public pressure to rescind new flight procedures that exposed some communities to increased noise [92]. Similarly, helicopter operations in New York, Los Angeles, and San Francisco have each been subject to community action to close heliports, set limits on the number or timing of flights, and alter flight paths [63,93,94]. General aviation (GA) airports such as Santa Monica have also been subject to impacts from community acceptance resulting in curfews, operational quotas, and/or the shortening/closing of runways and facilities.

UAM aircraft may conduct frequent operations to TOLAs sited within communities that have traditionally experienced low levels of aircraft noise. Fifty-six percent of the reference missions exhibited flight segments (including arrivals or departures) at altitudes below 500 ft over residential or tourist areas. Considering the degree of influence that local communities have historically had upon aircraft overflight, UAM operators may face scale limitations from community acceptance of aircraft noise generated by their operations [95].

Fig. 12 displays the pathways through which local communities may constrain the scale of UAM operations in response to noise exposure.



** An Environmental Impact Statement (EIS) is mandated by the US Congress through the National Environmental Protect Act*

Fig. 12 Pathways through which aircraft noise exposure can restrict aircraft operations.

In the first pathway at the top of Fig. 12, local communities may work through their municipal governments to use zoning and building codes to influence TOLA development and operations. These actions may prevent the development of TOLAs altogether or create operational restrictions for UAM, such as curfews and noise abatement procedures. The closure of Boston's HubExpress heliport in Cambridge and the reduction of New York's helicopter tour operations are examples of this pathway.

In the second pathway, local communities may work through their congressional representatives to compel the FAA to change ATC procedures, refuse funding for new TOLAs, or adjust aircraft noise certification requirements. The Los Angeles Residential Helicopter Noise Relief Act of 2013 [93] is an example of this pathway in action. The act required the FAA to develop new helicopter routes to reduce noise, develop a reporting system for noise complaints, and evaluate other means to reduce noise in the Los Angeles area.

Landowners may directly prohibit landings on their property through the third pathway. Landowners may also file lawsuits through the court system against overflights that they perceive to degrade their quality of life or the utility of their property. Chapter six of [42] provides a detailed review of the legal history of lawsuits against overflight.

Of the three pathways presented in Fig. 12, municipal government restriction of TOLA development and operation has most frequently limited previous helicopter operations. This pathway was therefore perceived as the most likely pathway through which community noise acceptance may constrain the scale of UAM operations.

Finally, despite the aviation noise restrictions implemented in some U.S. cities, the sensitivity of communities to aircraft noise appears to vary with location [96]. The successful implementation of extensive helicopter-based UAM operations in São Paulo without limitations from the public suggests that local values and expectations influence the actual severity of this constraint. Appendix A presents a review of literature on community acceptance of aircraft noise to investigate the variation of UAM noise impacts with location and their implications for mitigation opportunities.

4.3.3 Air Traffic Control (ATC) Services

ATC is not currently a significant limitation for helicopter or small aircraft operations in most cities. However, if UAM substantially increases the volume and density of flights occurring in a region then then capacity limits of ATC are likely to constrain UAM scaling through two pathways.

First, ATC is currently a human-centric system which is scale-limited by the workload capabilities of controllers and their supporting infrastructure. Pilots communicate with controllers through voice-based radio networks. These communications are not only inefficient requiring as much as 50% of a controller's time to convey routine information [97], but the radio frequencies can also only support one conversation at a time and may become saturated at high aircraft volumes. Midway and O'Hare airports each developed a separate radio frequency and controller position to handle approximily 135 helicopter flights per day in the 1960s [69]; UAM scale could similarly be restricted to this number of flights or less without adjustments by ATC.

Furthermore, human controllers may also become saturated when their cognitive load exceeds their personal comfort level to provide the required ATC services. The number of aircraft a single controller may handle varies with the complexity of the task. The monitor alert parameter (MAP) is used by the FAA to estimate staffing requirements and assumes a controller dedicates and average of 36 seconds of attention to each en-route flight [98]. Increasing the volume of UAM operations in a controlled airspace beyond a few flights at a time may therefore exceed a controller's workload capacity and lead them to delay or reject UAM access to the airspace [60].

The human-centric nature of ATC therefore presents potential scale limits for UAM flights that must interact with controllers. 94% of the reference missions used a TOLA located within a controlled airspace where the pilot would be required to communicate with a controller. This finding is interesting because even though controlled airspace only overlies a small minority of the land area within the case study system boundaries in Fig. 6, the locations of customer demand were nearly universally within the controlled airspace. Chapter 9 investigates this trend further and its implications for UAM scaling in the 34 largest U.S. metropolitan areas.

The second pathway through which ATC may constrain UAM operations is separation minima. Current separation requirements to surface obstacles and other aircraft limit where UAM routes may be developed and the throughput each route may support. VFR flights within controlled airspace and IFR flights in any airspace may be subject to separation minima on the order of miles. When applied, these large separation minima limit the density of UAM operations in a region, reduce access to nearby TOLAs, and constrain system scale [33]. However, VFR UAM flights that occur outside of controlled airspace may self-separate with no prescribed minimum spacing requirement.

IFR separation requirements may limit UAM operations even more severely at TOLAs that are not covered by conventional radar systems or served by an ATC tower. IFR UAM flights to these facilities are restricted to a one-in/one-out operational policy. Under this policy ATC authorizes only one aircraft to use a runway, approach procedure, or departure procedure at a time.

Due to the short duration of UAM missions and the limited flight endurance of fully electric UAM aircraft (if utilized), ground or airborne delay prescribed by ATC may impact the viability of UAM service and its scaling potential. Even a short delay by ATC to manage traffic congestion or workload saturation may result in a limited-range UAM aircraft diverting to an alternate TOLA for energy management or the loss of time savings compared to surface transportation modes irrespective of aircraft type.

Finally, the ATC constraint is especially challenging in that UAM operators have little direct influence to mitigate its impacts. The FAA is the primary stakeholder and decision maker for ATC regulations. As such, a regulatory and policy making process must be followed to increase the scale of UAM flights in ATC-managed airspace.

4.3.4 Safety and Certification

Safety, including the certification of new aircraft types, is a potential scaling constraint for UAM. Safety issues may trigger the community acceptance constraint [99], directly result in the vehicle grounding by the FAA, and/or reduce customer demand for the service. Both New York Airways and Los Angeles Airlines experienced a reduction of customer demand following a series of fatal accidents, and New York City also prohibited rooftop helipad operations due to an accident that resulted in the death of a bystander on the street-level.

Due to historical safety issues concerning helicopters as well as their high noise generation and operating costs, some prospective UAM operators propose to operate with newly developed aircraft [5,22,27]. The development of a new aircraft does not lessen the influence of the safety constraint on UAM. Rather, the certification of a new aircraft adds an additional potential restriction for UAM operations concerning the availability of aircraft. Furthermore, the vast majority of new vehicles proposed for UAM are hybrid or fully-electric aircraft with non-standard configurations. These qualities likely exacerbate the timeline and expense of certification.

The safety analysis of airworthiness required to support the certification of emerging electric aircraft is beyond the scope of this thesis. However, Ref. [65] may be consulted for more detail on the topic. At a high level, the certifiability of fully-electric aircraft is unclear due at least in part to the potential for a common mode power failure or a battery thermal runaway. Aircraft configurations that support gliding or autorotation were suggested by the author of [65] to have lower certification risk.

This thesis did not address the safety and certification constraint further. Both conventionally powered and electrically powered aircraft were considered where relevant.

4.3.5 Pilot Availability

Pilot staffing is a potential scaling constraint for UAM networks. Recent reviews of the professional pilot supply pipeline correlated a decline in new pilots entering the U.S. market to international competition and a reduced rate of professional advancement [100]. Table 8 presents the current U.S. pilot pool according to the FAA Airmen Certification Database. UAM operators may utilize either commercial or airline transport certified pilots for Part 135 (air taxi) operations.

Table 8 Current U.S. Pilot Pool

Pilot Rating	Pilot Certification		
	Commercial	Airline Transport	Total (unique pilots)
Fixed-wing*	178,000	119,000	199,000
Helicopter	26,000	5000	30,000

**either single engine land and multi-engine land ratings*

One potential UAM operator has proposed that as many as 1000 pilots would be required in order to operate a fleet of 500 aircraft in a single city [70]. If these pilots must be rated for a helicopter, then a single UAM system of this scale would require approximily 3% of the nation's existing pilots. Although the pilot pool is nearly seven times larger if UAM aircraft may be operated by fixed-wing rated pilots, these pilots are in high demand for commercial airline operations.

A variety of proposals to acquire sufficient piloting capabilities have been put forth from the UAM industry. First, some prospective operators have noted that there currently exist few opportunities for retiring military helicopter pilots to fly commercially. While this may be the case, the current pilot shortage is now prompting regional airlines such as Envoy Air to compete for retiring military helicopter pilots through their "rotor transition program".[8] Programs such as this not only provide support for retraining, but also offer a direct transition pathway into the high-paying flight decks of mainline airlines.

Refs. [100,101] correlate the decline in new pilots entering the U.S. airline market to a perception that professional advancement opportunities have stagnated and that foreign opportunities provide faster promotion and compensation. UAM operators may therefore have difficulty attracting pilots as there is not a clear advancement pathway to a mainline airline from a UAM service. Furthermore, UAM recruiters may face competition from existing helicopter operators in the emergency medical service, public safety, fire-fighting, private charter, and tourism industries.

Recognizing the challenge of pilot availability, NASA has conducted extensive exploration into the concept of simplified vehicle operations (SVO) [21] as an approach to reduce the training requirements for new pilots while maintaining at least an equivalent level of safety. Researchers at the Logistics Management Institute [21] proposed a transition pathway from an on-board, commercial pilot to a remote pilot and ultimately to a passenger with minimal or no pilot training as increasing levels of autonomy become certified.

The pilot availability scaling constraint was not considered further in this thesis. Low-volume, near-term UAM operations will likely provide services to price-insensitive markets. As such, sufficient pilots could be drawn from the existing pilot pools through competitive salaries. Furthermore, the constraint does not vary substantially with service location and long-term mitigations would be applicable to any city UAM is deployed in.

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[8] Envoy Air rotor transition program: www.envoyair.com/pilots/rotor-transition-program/

4.3.6 Logistics of Network Operations

UAM networks face logistical challenges that are unique compared to conventional aviation systems. These logistical challenges may limit UAM scaling by increasing costs and reducing network capacity.

Customer demand for commuter UAM services is highly directional. Individuals generally commute into commercial and industrial areas during the morning and then return to residential areas during the evening. Unidirectional travel demand during these periods may result in aircraft accumulating in areas of low consumer demand; this is known as a network balancing problem.

Network imbalance requires non-revenue “deadhead” flights to return aircraft from areas of low demand to high demand. As an initial order of magnitude estimate of the deadhead ratio UAM may experience, automobile ride-hailing networks have an estimated 20% - 50% deadhead ratio [47]. High deadhead ratios expend a large portion of network capacity on flights that generate no revenue.

The short duration of UAM flights mean that UAM aircraft will need to be staged at TOLAs between peak operating periods unlike commercial aircraft which often fly long-legs overnight or during midday. The development of aircraft parking may be challenging at footprint-constrained TOLAs in urban areas. As a result, additional staging TOLAs may be necessary requiring re-positioning flights to the customer TOLAs.

Furthermore, while previous helicopter airlines achieved gate turnaround times of one to three minutes when they did not refuel between flights [12], fully electric aircraft may require on the order of ten or more minutes for charging between each flight. Longer turnaround times may lead to changes in TOLA operations including the repositioning of aircraft from gates to staging stands for charging or the development off-site charging depots.

Lastly, the ability of UAM networks to tolerate delay and off-nominal operations may be diminished compared to the current national airspace system. Conventional aircraft are frequently assigned airborne holding when an airport’s arrival capacity is reached. However, airborne delay may not be feasible for energy-constrained, fully electric aircraft. Furthermore, in the case of off-nominal operations due to weather or emergencies, a UAM network has a shorter time horizon in which to coordinate diversions and limit cascading delays. In order to address these limitations, UAM network operations may have to arbitrarily reduce throughput in order to provide greater buffer for operations and increase the system’s stability.

This thesis did not directly evaluate UAM network management, but sought to develop a refined understanding of TOLA and ATC performance in order to support future work on operational planning for UAM logistics.

4.3.7 Weather Restrictions

Adverse weather may constrain the scale of UAM operations in a variety of ways. Low visibility, high winds, or poor runway conditions (due to precipitation, for example) may hinder operations at a TOLA or require higher performance aircraft and equipage. Low visibility may reduce flight density due to larger ATC separation minima. High temperatures may reduce aircraft performance and are especially detrimental to battery and engine thermal management on electric aircraft. Finally, icing conditions or convective weather may prevent UAM flights.

Chapter 9 presents an analysis of the frequency of IMC, convective weather, and extreme temperatures for the 34 most populous metropolitan areas in the United States. While convective weather and extreme temperatures may reduce aircraft performance and the ability to operate in any airspace, IMC may impact UAM scale potential due to ATC restrictions rather than aircraft capabilities. The relation between weather restrictions and ATC services is explored further in Chapter 6.

4.4 Constraint Selection for Further Evaluation

The TOLA availability and ATC services constraints were selected for more detailed evaluation in the remainder of this thesis. Based upon the exploratory case study results and the discussion presented above, both of these constraints will influence the majority of UAM missions in a given city and restrict scaling beyond a small number of operations.

Furthermore, many of the other constraints impact UAM scale by acting on either TOLAs or ATC. Community acceptance primarily influences the ability to develop or operate TOLAs. Poor weather conditions affect UAM scale by requiring larger ATC separation minima or preventing arrivals and departures at TOLAs due to visibility minima.

The TOLA and ATC constraints were also interesting in that their severity varies with location. Variation in the severity of a constraint with location is important because it implies that a single mitigation is unlikely to work for all cities. Furthermore, some cities and areas may be more attractive for near-term UAM implementation where the operational constraints are less severe.

For example, the number of existing heliports and airports in São Paulo far exceeds that of Seattle. Furthermore, development of new TOLAs is likely to be more difficult in New York than Dallas due to the former's local zoning policies and greater sensitivity to helicopter operations. In terms of ATC, restrictions due to national security preclude nearly any UAM flight in Washington, DC, while UAM does not have to interact with ATC in the majority of Indianapolis.

4.5 Detailed Constraint Analysis

The remaining chapters of this thesis investigate TOLA performance and ATC services in more depth.

Chapter 5 investigates the development and operation of new TOLAs in urban areas. To support the scaling of UAM flights it is advantageous for TOLAs to have a small footprint to enable siting near demand, but it is also necessary for the TOLA to support a large throughput capacity for aircraft and passengers. The tradeoff of these design goals is presented.

Chapter 6 investigates how ATC limitations may constrain the scale of UAM operations. UAM operations to TOLAs located near airports are found to significantly limit UAM operations. Chapters 7 and 8 explore strategies to support higher volume UAM operations near airports in visual and instrument conditions. Finally, Chapter 9 evaluates the variation of UAM scaling potential in the largest 34 metropolitan areas by population in the United States as a function of ATC.

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5 Takeoff and Landing Area Availability for UAM

The exploratory case studies in Chapter 4 found that while Boston, Los Angeles, and Dallas each had over 200 heliports and airports, these existing facilities may not effectively support UAM operations. The development of new TOLAs was therefore considered to be an enabling requirement for UAM scaling. In line with this, TOLA development was proposed as the "greatest operational barrier to deploying [UAM] in cities" by the 2016 Uber white paper on UAM [5].

In order for a UAM system to increase the scale of its services, new TOLAs are required that:

1. are conveniently accessible to customers, and
2. provide sufficient passenger and aircraft throughput to support scaling.

The most challenging location to develop TOLA infrastructure with these qualities is in dense urban locations where available space is limited, buildings or other obstructions may block approach and departure paths, and large populations may be exposed to aircraft noise.

This chapter investigates the development of TOLA infrastructure with a small footprint but a large throughput capacity as an enabling capability for UAM scaling.

Previous studies by Georgia Tech [67,90,102] and MIT [41] suggest that substantial opportunity exists to site UAM TOLAs in urban areas if their footprint is less than approximately 500 ft in the longest dimension. The smaller the footprint of the TOLA, the greater the opportunity to site it near customer demand. However, previous literature did not address the aircraft throughput capacity of TOLAs as a function of footprint.

The analysis of TOLA operations and findings presented in this chapter complement the previous literature by:

1. developing an analytical model to estimate aircraft throughput for a TOLA,
2. determining the sensitivity of aircraft throughput to the design of the TOLA and the operating conditions, and
3. identifying TOLA topologies that maximize throughput for a given footprint and operating condition.

5.1 Approach

This chapter followed a three-step approach to characterize the throughput potential for footprint-constrained TOLA infrastructure.

Step 1: TOLA Footprint Estimation

Estimates of the physical footprint required to host a TOLA with an arbitrary number of gates, runways/pads, and staging stands were developed. High-capacity heliports were evaluated to identify different strategies to arrange the components of the TOLA and manage aircraft operations among them. This led to the definition of four TOLA topologies with unique arrangement characteristics and footprint implications, namely a linear topology, a satellite topology, a pier topology, and a remote apron topology. Vertiport and heliport design standards were reviewed to estimate the footprint required for TOLAs of each topology. Footprint estimates were developed for VTOL infrastructure in order to determine a lower-bound for required footprint (assuming STOL infrastructure would be larger due to increased ground roll).

Step 2: Throughput Capacity Estimation

An analytical model of TOLA operations was developed to estimate the deterministic aircraft throughput of a given facility. TOLA operations were modeled as a multi-commodity flow network where nodes in the network represent physical components of the TOLA (gates, runways/pads, and staging stands), links represent aircraft performance characteristics, commodities represent aircraft of different types, and flow constraints represent operating policies.

The network was then formulated as an integer program (IP) and solved for varying objective functions to determine the throughput capacity envelope of the TOLA. Tradespace exploration was conducted to determine how TOLA throughput varies with aircraft performance and TOLA design attributes. The most sensitive aircraft and TOLA attributes are the key variables for a designer to consider to increase TOLA throughput. The network model of TOLA operations and tradespace exploration findings were applicable to both VTOL and STOL operations.

Step 3: Case Studies of Throughput for Footprint-Constrained TOLAs

An estimate of potential throughput was developed for two case studies with representative inner-city footprints of 300 ft by 300 ft and 200 ft by 500 ft. TOLAs with the linear, satellite, and pier topologies were developed for both case studies; the remote apron topology was not considered in this analysis due to its large footprint requirements.

The throughput of each TOLA was estimated in five operating conditions. Three of the operating conditions represented VFR scenarios with inter-arrival times between aircraft of 30 s and aircraft turnaround times varying from 60 s to 300 s. The other two operating conditions represented IFR scenarios with inter-arrival times of 90 s and aircraft turnaround times of 60 s and 300 s. ATC lateral separation minima for VFR and IFR operations were applied to the scenarios.

Findings indicated which topology enables the largest throughput for footprint-constrained TOLAs in various operating conditions. Furthermore, findings identified attributes of TOLA operations that are critical to throughput and influence the TOLA’s design. The case studies did not consider the influence of winds, ATC, or stochasticity in aircraft operations on TOLA throughput. Furthermore, passenger operations and facilities (including terminal space and walkways) were also not considered. These factors may influence the feasible throughput capacity and footprint of the TOLA topologies. An assessment of the robustness of TOLAs to these additional factors is suggested for future work.

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Generic TOLA ConOps

The ConOps for a generic TOLA is presented in Fig. 13. The ConOps represents operations for either VTOL or STOL aircraft, is applicable to a TOLA with any number of infrastructure components (i.e., gates, staging stands, or runways/pads), and may represent the arrangement of those components in any configuration (i.e., topology).

In Fig. 13, arriving aircraft are first held in a queue until authorized to conduct the final approach. Aircraft then arrive to one or more touchdown and liftoff (TLOF) pads through the use an arrival procedure(s). A TLOF pad may be a helipad for VTOL aircraft or a runway for STOL aircraft. If the TOLA is equipped with gates then the aircraft may taxi off the TLOF pad to an available gate; if no gates exist then the aircraft conducts the turnaround on the TLOF pad. Taxiways may either be bidirectional (i.e., supporting simultaneous aircraft taxiing in either direction) or unidirectional (i.e., supporting aircraft taxiing in only one direction at a time).

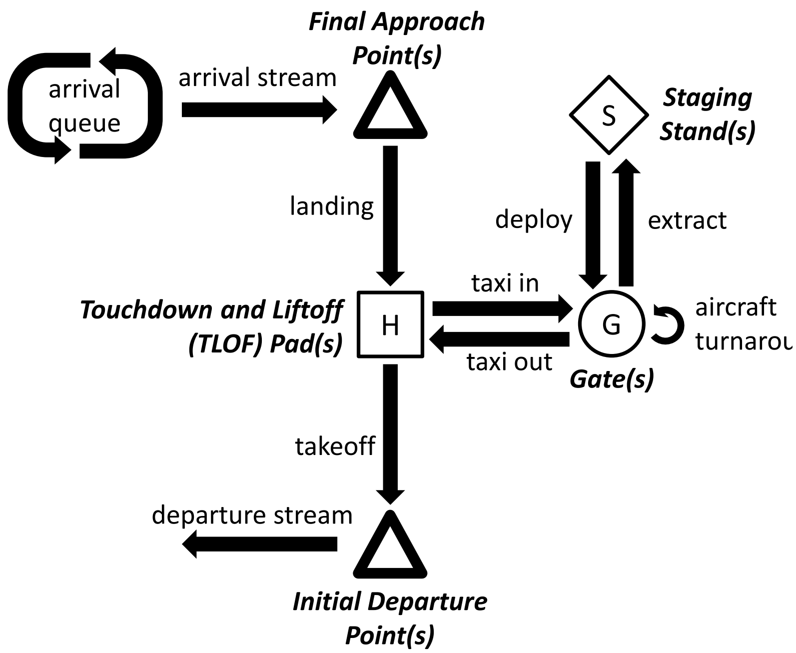


Fig. 13 Generic TOLA ConOps.

Aircraft turnaround is defined as the process or completing an aircraft's arrival and then preparing the aircraft for its next departure. Turnaround may involve unloading passengers and baggage, fueling/charging the aircraft, cleaning the cabin, replenishing consumables, and/or loading new passengers and luggage; not all of these activities must occur during each turnaround. Once the turnaround is completed, the aircraft may taxi to the same or a different TLOF pad and depart through one or more departure procedures.

A TOLA may also be equipped with staging stands. These are parking areas such as aprons, ramps, hangars, or other airfield space where aircraft may be stored. It was assumed that no turnaround activities may occur at staging stands. If staging stands are available at the TOLA, then aircraft may also be prepositioned on the stands and deployed into service. Alternatively, aircraft may be extracted from service to the staging stands. As discussed in Chapter 4, staging capacity may be especially important for UAM operations in order to manage unidirectional customer demand and temporal variation of demand. The ConOps presented in Fig. 13 also enables the staging of aircraft at gates.

Finally, although not indicated in Fig. 13, aircraft operations at the TOLA including landing, taxiing, and departing may or may not be authorized to occur simultaneously (i.e., they may be dependent operations). Independence between two TLOF pads is a function of separation requirements and procedure design while the independence of taxiways is dependent on facility design and operating procedures.

5.2 Footprint Estimation for UAM TOLAs

The physical footprint of a TOLA depends upon the number of gates, stands, and TLOF pads it supports, the required size of each of these components, and how they are physically arranged and connected by taxiways (i.e., their topology).

5.2.1 Review of High-Throughput Heliport Operations

Current design standards lay out the requirements for infrastructure component sizing. However, the standards do not provide guidance for how these components may be arranged to support maximum aircraft throughput for a minimum footprint.

To begin to address this question, 27 high-capacity heliports were evaluated to assess their physical topology and how aircraft operated on them. The number of each infrastructure component at each heliport is presented in Table 9. The TLOF pad to gate ratio varies significantly between the facilities. This variation was anticipated to result from different purposes of the facilities. Some heliports, such as those for military operations or maintenance and overhaul, prioritized staging capacity and gates. Other heliports, such as those located at sports venues or within city centers, prioritized a larger number TLOF pads. It was anticipated these topology differences created different throughput and staging capabilities.

The arrangement of the physical infrastructure at the heliports in Table 9 also varied between facilities. The heliports were grouped into four topologies as indicated in the final column of the table.

Fig. 14 displays an example of the linear topology where two or more TLOF pads are arranged in a line with few or no gates associated with each. Arrivals and departures from each TLOF pad may or may not be independent. Arrivals or departures typically occur perpendicularly to the line of TLOF pads.

Fig. 15 is an example of the satellite topology where gates are arranged circumferentially around one or more TLOF pads. Arrivals and departure may occur from any direction; however, aircraft may not be stationed on gates below overflying aircraft.

Fig. 16 displays an example of the pier topology where one or more TLOF pads are connected to a corridor of gates through a taxiway. Lastly, Fig. 17 displays a heliport representative of the remote apron topology where a TLOF pad(s) is located separately from the gates and staging areas. A potentially long taxiway connects the pieces of infrastructure.

Table 10 provides further information on each TOLA topology.

Table 9. Heliport topology review.

Heliport	TLOF Pads	Gates	Staging Stands	Topology
Dallas Downtown Public Heliport, TX	2	5	0	Satellite
Monaco Heliport, Monaco	8	0	14+	Linear
Los Angeles Hooper Heliport, CA	2	16	0	Pier
Haungzhuangcun Air Base, China	44	40	80+	Remote Apron
Los Angeles Airport Heliport (2015), CA	2	8	0	Pier
Portland Downtown Heliport, OR	1	4	0	Satellite
Silverstone Heliport (2018), England	10	0	0+	Linear
Downtown Manhattan Heliport, NY	1	13+	0	Pier
Manhattan East 34th St. Heliport, NY	4	0	0	Linear
Manhattan West 30th St. Heliport, NY	10	0	2+	Linear
NYPD Air Operations Heliport, NY	1	4+	9+	Pier
Helo Holdings Inc. Heliport, NJ	2	6	22+	Pier
Dempsey Army Heliport (1977), TX	12	500	50+	Pier
Redmond Taylor AHP Heliport, TX	8	19	12+	Remote Apron
Dallas Cowboys Heliport, TX	1	2	0	Satellite
London Heliport, England	1	3	0+	Pier
Gagetown Heliport, New Brunswick	1	14	5+	Pier
Helicidade Heliport, São Paulo	2	11	80+	Satellite
Helipark Heliport, São Paulo	1	10	200+	Pier
Aeroporto Campo de Marte, São Paulo	1	82+	250+	Remote Apron
Auckland Heliport, New Zealand	4	0	7+	Linear
Balikpapan Airport, Indonesia	2	15	20+	Pier
Shimotsuma Heliport, Japan	1	2	20+	Pier
Northwest Helicopter Heliport, WA	1	16	30+	Pier
Airjamban Heliport, Indonesia	7	4	15+	Linear
Rohini Heliport, India	3	12	16+	Pier
Picacho Stagefield Heliport, AZ	4	16	0+	Pier

"+" indicates that additional non-marked, ad-hoc staging stands may be available

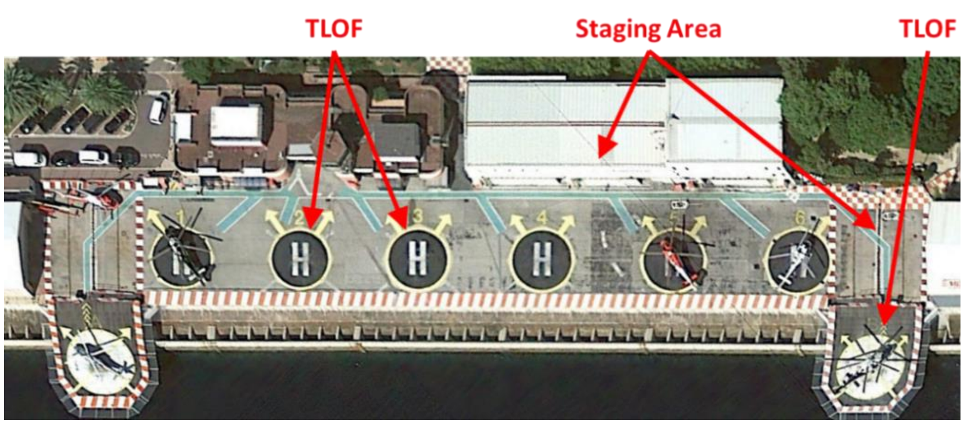


Fig. 14 Monaco heliport displaying attributes of a "linear" topology.
Map © 2018 Google. © 2018 DigitalGlobe.

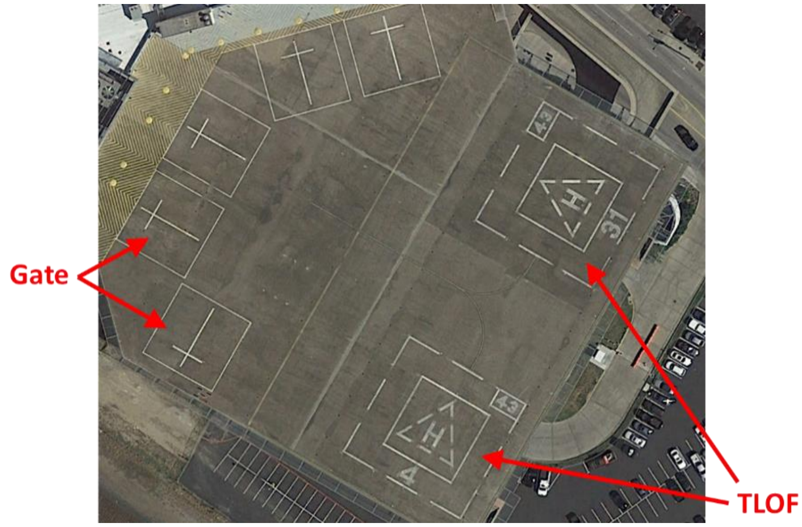


Fig. 15 Dallas downtown public heliport displaying attributes of a "satellite" topology.
Map © 2018 Google.

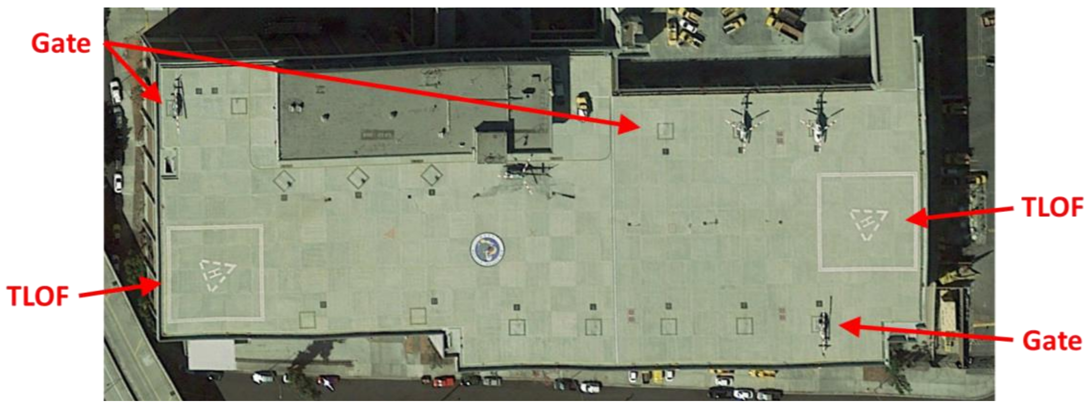
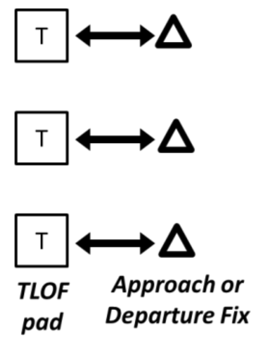
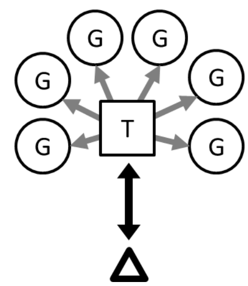
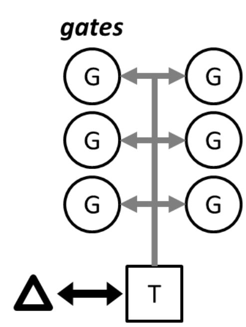
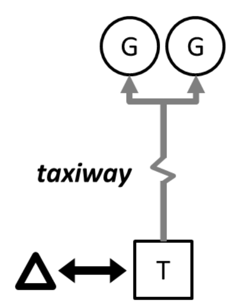


Fig. 16 Los Angeles Hooper Heliport displaying attributes of a "pier" topology.
Map © 2018 Google.

Fig. 17 Aeroporto Campo de Marte displaying attributes of a "remote apron" topology.
Map © 2018 Google. © 2018 DigitalGlobe.

It was anticipated that the topologies would result in different footprint efficiencies, throughput capacities, and noise exposure to communities, among other factors. Table 10 describes the four topologies. The topologies were named consistently with airport layouts as presented in [103].

Table 10. TOLA topologies.

Description	Diagram
Linear Topology *(Fig. 14)* Multiple TLOF pads are arranged linearly to support UAM operations directly to or from them (though not necessarily simultaneously). The TLOF pads are typically not connected to gates. Aircraft turnaround is conducted on the TLOF pad. The availability of multiple TLOF pads adds operational flexibility to handle off-nominal operations or clustered (rather than well-sequenced) operations. The linear topology is most useful when vehicle turnaround times are short and where there is a thin but long available footprint such as a highway or railway right of way.	
Satellite Topology *(Fig. 15)* One or more TLOF pads are associated with gates distributed circumferentially around them. Gates located underneath the flight path are not usable. The satellite topology is the most compact layouts and its form factor (roughly square) lends itself to potential implementation on rooftops or land parcels in urbanized areas with a gridded street layout.	
Pier Topology *(Fig. 16)* One or more TLOF pads feed aircraft into a corridor of gates of arbitrary length. The pier concept can physically accommodate more gates and aircraft than the satellite layout providing benefits for TOLAs with long vehicle turnaround times or the need to stage multiple aircraft onsite. The pier topology is not well suited for small footprint TOLAs, however, due to the size requirements of the taxiway. Pier topologies with two TLOF pads may simplify surface operations by enabling unidirectional taxiway flow from a dedicated arrival pad to a dedicated departure pad.	
Remote Apron Topology *(Fig. 17)* One or more TLOF pads are located separately from the gates and may require significant taxiing between them. This topology may support simultaneous takeoffs and landings if sufficient lateral separation is provided between TLOF pads. The remote apron concept requires a large footprint to implement, but does not require physical taxiway infrastructure if aircraft can hover or air taxi over unimproved areas. This topology is best suited to support simultaneous IFR arrivals as TLOF pads may be widely separated from one another.	

5.2.2 Size Requirements for TOLA Components

The size requirements of TLOF pads, gates, staging stands, and taxiways were estimated based on heliport design standards. It was assumed that UAM TOLAs will have design requirements similar to those prescribed for general aviation, VFR heliports in FAA Advisory Circular (AC) 150/5390-2C. Based upon the review of seven UAM vehicle concepts presented in Table 11, a representative aircraft with a maximum tip-to-tip span (TTS) of 45 ft was considered as the reference design vehicle.

Table 11 Review of seven proposed 2-6 passenger eVTOL aircraft.

Vehicle	PAX	Configuration	Tip-to-Tip Span (ft)	Body Dimension (ft)	Max Dimension (ft)
A^3 Vahana Beta	2	Tilt Wing	28.5 *est.*	20.6 (wingspan)	28.5
AirSpaceX MOBi	4	Tilt Wing	40	40 (wingspan)	40
Carter Air Taxi	6	Compound Heli	45	42 (wingspan)	45
Joby S4	4	Tilt Rotor	43 *est.*	35 (wingspan)	43
Aurora (June 2017)	2	Lift + Cruise	29.2 *est.*	26.2 (length)	29.2
Kitty Hawk Cora	2	Lift + Cruise	33.5 *est.*	35 (wingspan)	35
Volocopter 2X	2	Multirotor	32 *est.*	30 (superstructure)	32

AC 150/5390-2C defines sizing requirements for TOLA components based on the rotor diameter of the reference design vehicle. However, the rotor diameter of emerging UAM aircraft with non-conventional configurations may be quite small. Therefore, the concept of “tip-to-tip span” defined as “the span (distance) between the extreme edges of the plane(s) generated by spinning rotors or proprotors” in the FAA’s retired AC for vertiports was used in lieu of rotor diameter [76]. Note that tip-to-tip span does not include propellers that do not provide vertical lift.

The estimated footprint requirements for TLOF pads, gates, and taxiways are presented in Table 12 based on a reference design aircraft with a tip-to-tip span of 45 ft. Staging stands that are accessed directly by an aircraft through rotor-powered taxiing have the same footprint requirements as a gate. Staging stands that aircraft are moved into or out of via a tug or wheel driven taxiing may have reduced footprint requirements.

Previous studies determined that hover taxiing exposes passengers to greater rotorwash and requires more energy expenditure. Ground taxiing was recommended for high throughput, public vertiport operations [104,105] and is assumed as the design standard for this study. Details of the footprint estimations in Table 12 may be found in Ref. [106] and are based on recommendations for general aviation, VFR heliports from AC 150/5390-2C.

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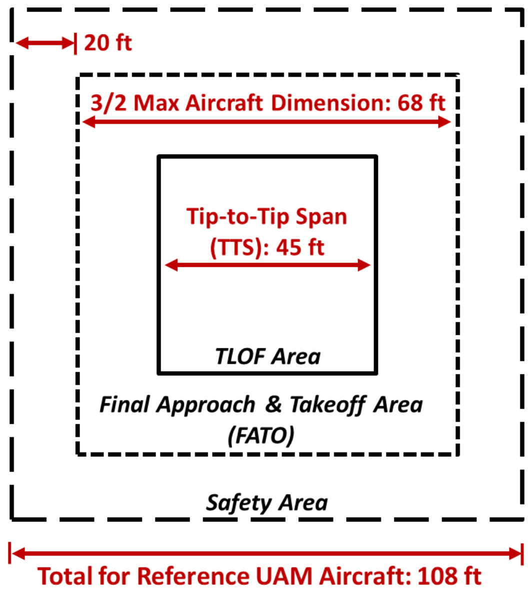
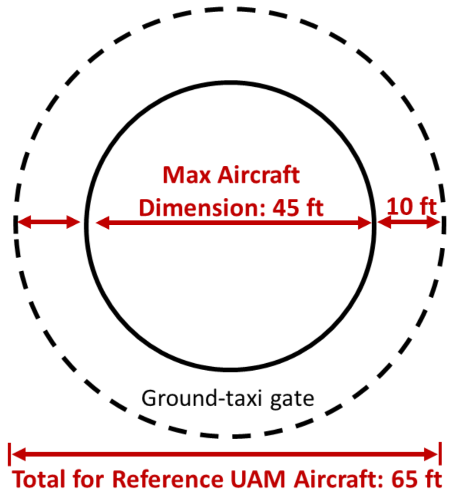
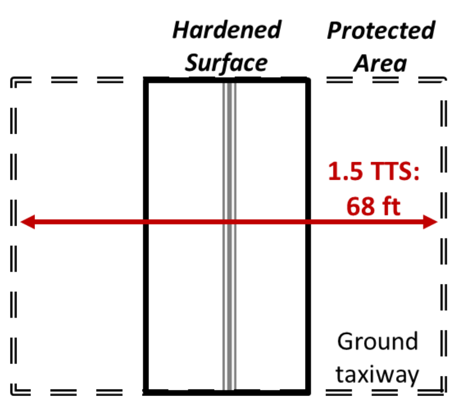
Table 12 Estimated dimensions of TOLA components for a 45 ft reference design aircraft.

TOLA Component Footprint Requirement	Image
<u>TLOF pads</u> TLOF pads for the reference design aircraft will require a footprint of 108 ft by 108 ft plus at least one unobstructed approach and departure path. The derivation of this sizing is shown in the image to the right. Only the central 45 ft by 45 ft must be a physical, load-bearing surface. One aircraft is allowed to reside within the safety area at a time [107]. To support simultaneous VFR arrivals and departures, TLOF pad centerlines should be separated by 200 ft [107,108]. Simultaneous IFR arrivals may generally not be supported to TLOF pads spaced less than 3000 ft. Chapter 8 discusses simultaneous IFR spacing requirements in greater detail.	
<u>Gates</u> The minimum diameter of a gate is equal to the maximum dimension of the reference design aircraft and either 20 ft for ground taxiing (65 ft total) or a third of the maximum aircraft dimension (15 ft) for hover taxiing (75 ft total). Ground taxi gates are assumed in this analysis. Gates must be positioned at least a third of the maximum aircraft dimension (15 ft) from a taxiway. The outer 10 ft of the gate is a safety area which may overlap with the safety area of other gates. All gates in this analysis are assumed to support UAM that turn around at the gate as opposed to backing out of or taxiing through the gate.	
<u>Taxiways</u> Ground taxiways must be one and a half times the aircraft tip-to-tip (TTS) span (68 ft) in width while hover taxiways must be two times the TTS (90 ft). The hardened surface of the taxiway must be two times the undercarriage in width, and the protected area must be free of obstacles and other TOLA components.	

5.2.3 Footprint Implications of Three TOLA Topologies

Footprint estimates were developed for TOLAs exhibiting three different topologies. The remote apron topology was a special case of the other topologies with an extended taxiway between the TLOF pads and the gates or staging stands; it was therefore not considered in this analysis. TOLAs may also be developed with layouts that are hybrids between the topologies presented below; their footprint must be considered accordingly. The footprint estimates were developed for a specific number of TLOF pads and gates. However, the additional footprint required to add further gates or TLOF pads to each topology is stated.

5.2.3.1 Footprint of a TOLA with a Linear Topology

Fig. 18 displays the footprint of a notional linear topology TOLA with two TLOF pads. Each TLOF pad may support simultaneous and independent VFR arrivals and/or departures as the centerline of each pad is separated by 200 ft [107,108]. Only one approach/departure path is required to TLOF pads designed based on general aviation, VFR heliport recommendations in AC 150/5390-2C, however two paths are recommended and required for transport category facilities. An advantage of the linear topology is it readily supports two approach/departure paths perpendicular to the row of TLOF pads.

The red dashed box encompasses the parts of the TOLA that must be physical, load bearing surfaces. The red box therefore represents the minimum physical footprint required to develop this TOLA and is 245 ft by 45 ft. The components of the TOLA outside the red box are areas that must be free from obstructions, but may be undeveloped surface or even open air (for rooftop facilities, for example). The minimum obstruction free footprint sizing is represented by the purple dashed box and is 308 ft by 108 ft. Additional independent VFR TLOF pads may be appended on either side of the TOLA and will each add an additional 200 ft to the width of both the physical and obstruction free footprints.

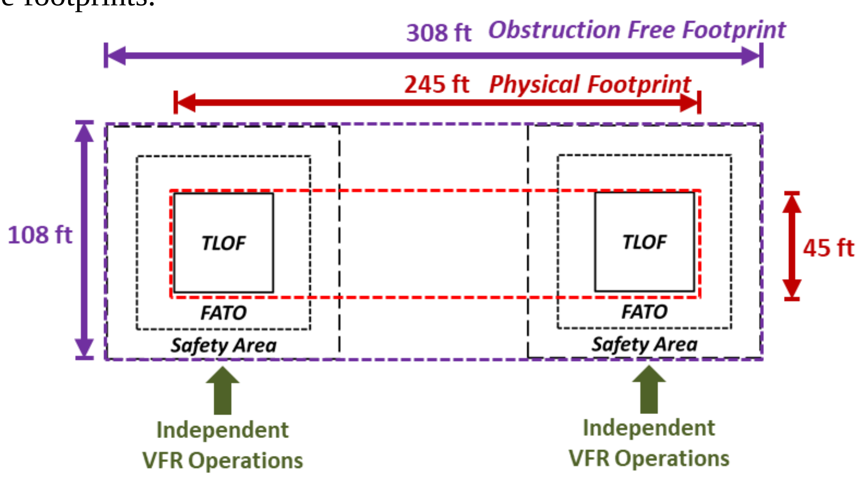


Fig. 18 Example linear topology footprint requirements for two independent TLOF pads.

An additional TLOF pad could be positioned in-between the two pads of Fig. 18 if they were separated by an additional 16 ft as shown in Fig. 19; this expansion is to prevent any part of the TLOF safety areas from overlapping. VFR operations to the center pad are dependent with operations on either of the outside pads because their centerline separation is less than 200 ft. The minimum physical footprint of this example facility is 262 ft by 45 ft, while the obstruction free footprint is 324 ft by 108 ft. Additional dependent TLOF pads may be added on either side of the

TOLA and will each add an additional 108 ft to the width of both the physical and obstruction free footprints.

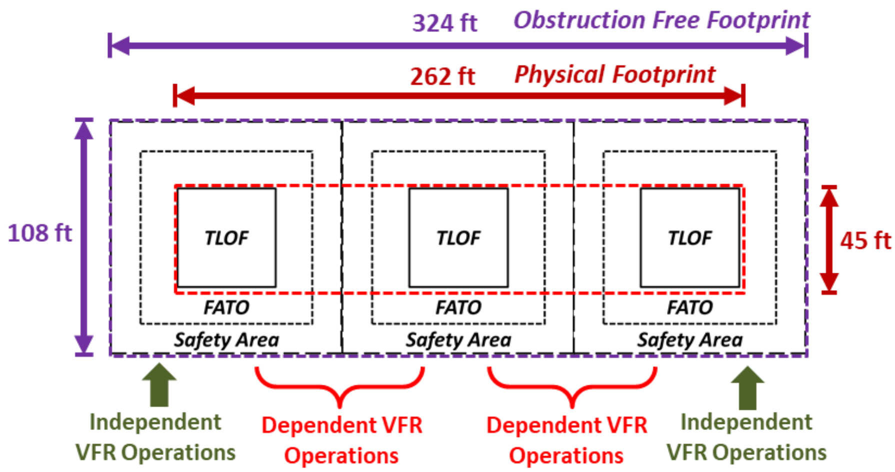


Fig. 19 Example linear topology footprint requirements for three TLOF pads.

5.2.3.2 Footprint of a TOLA with Pier Topology

Fig. 20 displays the footprint of a notional pier topology TOLA with one TLOF pad and four gates based on the component dimensions introduced in Table 12. Gates must have 10 ft between them and any other gate, although their safety areas may overlap. A taxiway must be located at least 15 ft from a gate (not including the gate's safety area). The taxiway is 68 ft in width and supports unidirectional ground taxiing (i.e., no passing). Any number of additional gates could be appended to the right or the left of the TLOF at a rate of two gates per 55 ft of additional width to the TOLA. Furthermore, two approach/departure paths may also be supported without overflying the gates.

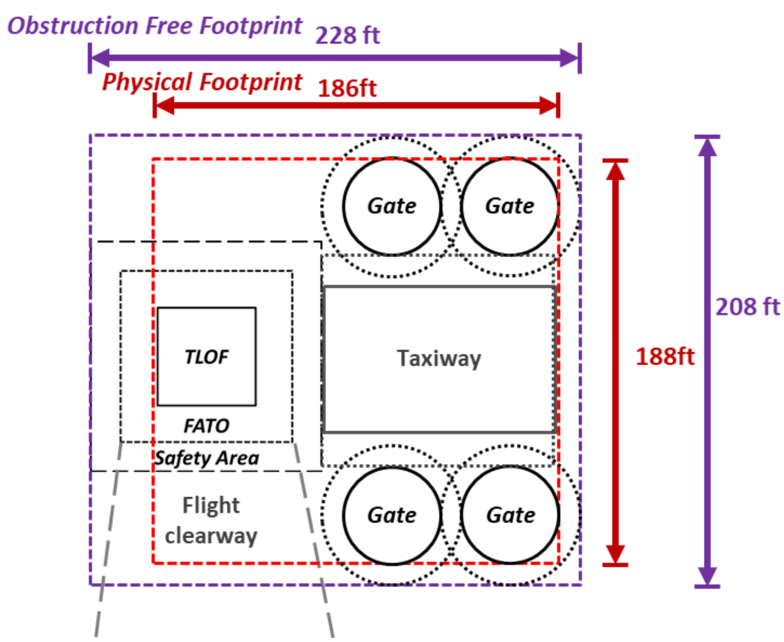
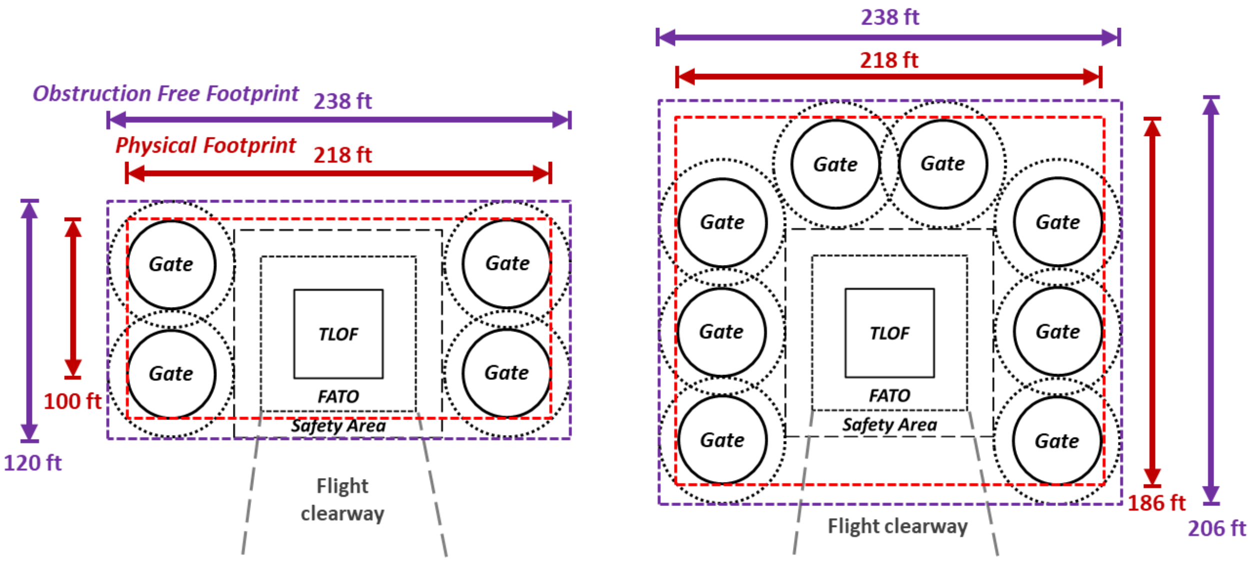


Fig. 20 Example pier topology footprint requirements.

5.2.3.3 Footprint of a TOLA with a Satellite Topology

Fig. 21 displays the footprint of two notional TOLAs with variations of the satellite topology. The first example is a compact layout with one TLOF pad and four gates. This layout may support two approach/departure paths in a fly-through configuration.

The second example increases the number of gates that may paired with one TLOF pad. The satellite topology more densely packs TLOF pads and gates than the pier topology as taxiways are not required. However, only one approach/departure path could be supported without overflying gates and would therefore require reverse flow procedures. If winds shift, arrivals or departure may overfly gates, however no aircraft may actively use the overflown gates.



Small footprint satellite topology *Increased gate to TLOF pad ratio satellite topology*

Fig. 21 Example satellite topology footprint requirements.

5.3 Tradespace Analysis of TOLA Throughput Capacity

An analytical model of TOLA operations was developed and deployed in a tradespace analysis to estimate the maximum deterministic aircraft throughput capacity for a given TOLA. Furthermore, the sensitivity of maximum aircraft throughput to design attributes of a TOLA and variations in its operations were evaluated.

A TOLA was characterized in the model through four *infrastructure variables*. Three of the infrastructure variables defined the number of TLOF pads, gates, and staging stands at a TOLA, respectively. The fourth infrastructure variable defined the taxiway links between the other three infrastructure components.

The operation of a TOLA was defined in the model through seven *operational variables* that represented the activities of aircraft on or near the TOLA. The operational variables were:

1. Aircraft Turnaround Time: the minimum time required at each gate to park the aircraft, spin down the rotors (if necessary), conduct various tasks (e.g., passenger/luggage unloading and/or loading, fueling/charging, etc.), and then exit the gate area.
2. Inter-Arrival Time: the minimum time between subsequent arrivals at one TLOF pad. The inter-arrival time is dependent upon the in-trail separation minima between aircraft, the approach speed, and the TLOF pad occupancy time, for example.
3. Inter-Departure Time: the minimum time between subsequent departures at one TLOF pad.
4. Gate Taxi Time: the minimum time required to taxi from the edge of a TLOF pad's safety area to a gate or vice versa.
5. Staging Stand Taxi Time: the minimum time required to taxi from a gate to a staging area or vice versa.
6. TLOF Pad Operating Constraint: a constraint that sets if aircraft may operate on adjacent TLOF pads independently, simultaneously, or dependently with one another.
7. Taxiway Operating Constraint: a constraint that sets if a taxiway supports unidirectional flow (i.e., no passing) or bidirectional flow.

Fig. 22 presents the relationship between the throughput capacity of a TOLA, its footprint, the infrastructure variables, and the operational variables. The results of this section enable the estimation of maximum deterministic throughput capacity based on the infrastructure and operational variables. The results from the Section 5.2 enabled the estimation of required physical and obstruction free footprints for a TOLA based on the infrastructure variables.

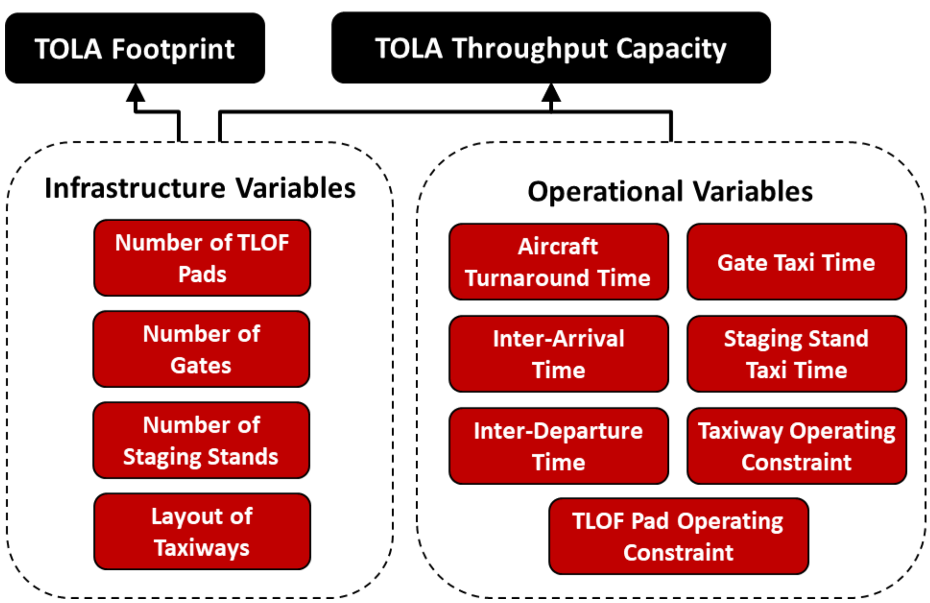


Fig. 22 Relationship of infrastructure and operational variables to TOLA throughput capacity and siting feasibility.

5.3.1 Integer Program Development for TOLA Operations

An integer program (IP) was developed for TOLA operations based upon the Bertsimas-Stock multi-commodity flow formulation proposed for traffic flow management [109]. The IP casts the TLOF pads, gates, and staging stands as nodes of the network flow model. The taxiways define the arcs of the model. The operational variables set the travel times or flow constraints for the arcs.

As a representative example, Fig. 23 presents the network flow representation of the Dallas Cowboys Heliport which is a TOLA with one TLOF pad, two gates, one set of approach and departure procedures, and an arbitrary number of (i.e., "N") staging stands.

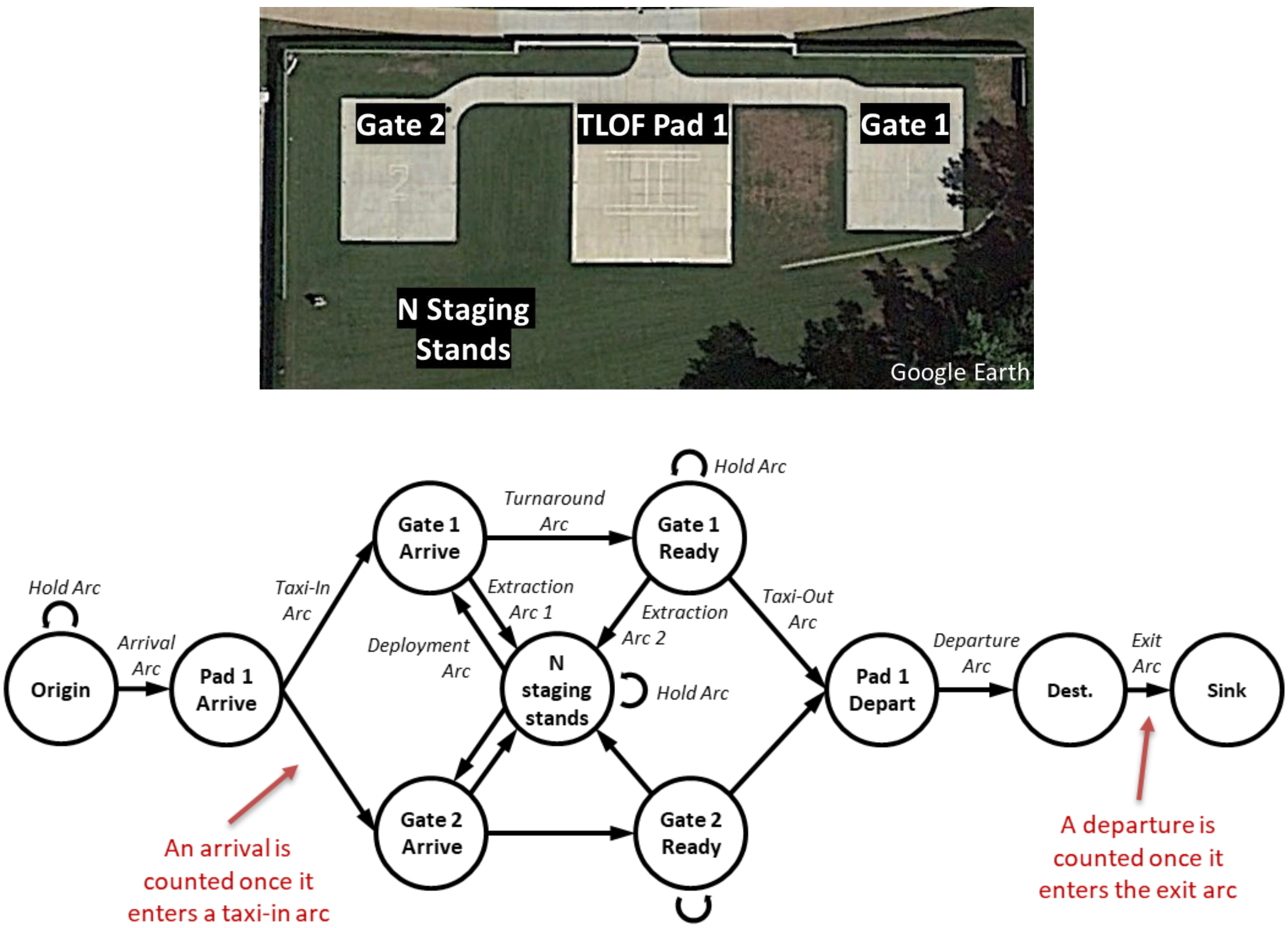


Fig. 23 Example TOLA with one TLOF pad, two gates, and "N" staging stands (top image) and its network flow representation (bottom image).

The "origin" and "sink" nodes represent aircraft entering from the arrival queue and departing into the surrounding airspace system, respectively. It was assumed that there was infinite ATC capacity and an aircraft may enter the origin or sink nodes at any time. TOLAs of different design may be represented through this network flow model by varying the number and configuration of the nodes and arcs to represent the topology and operations of the TOLA. Furthermore, transient operating conditions may be represented by "staging" aircraft on the staging stand or gate nodes.

It may be noted in Fig. 23 that the TLOF pad was represented by two different nodes. The first node represents the state when an aircraft arrives on the pad, and the second node represents when it departs from the pad. The model was constrained to only allow one arrival or departure at a time to the nodes representing the same TLOF pad. Each gate was similarly split into two nodes.

Each arc was associated with a travel time required for the aircraft to traverse it. These travel times correspond to the operational variables. All arcs were unidirectional and were generally limited to a capacity of one aircraft. The "hold" arcs at the origin and staging nodes may have capacities of greater than one to represent aircraft waiting in the arrival queue or in staging, respectively.

An IP was formulated to optimize aircraft flow through a given TOLA network (such as the one presented in Fig. 23) subject to an objective and the model constraints. At a high level, the IP assigned aircraft to each at every time step of the simulated period in order to maximize the value of its objective. More formally, the *decision variables* of the IP were the number of aircraft of each commodity that enter each arc at each time step.

The *objective* of the IP was to maximize value where a reward is specified for each arrival and departure completed. Fig. 23 displayed that an arrival was rewarded the moment an aircraft completed the arrival arc and transitioned to the taxi-in arc. A departure was rewarded the moment an aircraft completed the departure arc and transitioned to the exit arc. Two award schemes for arrivals and departures were used to define the TOLA's capacity envelope; these award schemes may be found in Appendix F.

The *constraints* of the IP ensured that physical realities were met (such as prohibiting two aircraft from simultaneously parking at a gate). Constraints also enforced the taxi and TLOF pad operating variables by controlling which arcs could simultaneously be occupied by aircraft.

The IP was formulated using the following variables:

- S = set of TOLA elements except the "sink" node
- $k(f)$ = aircraft type of flight f (i.e., the commodity type)
- $N(k)$ = set of arcs that aircraft of type k can use
- $C_i(t)$ = capacity of TOLA element i at time t
- $t_{i,j}$ = travel time on arc (i,j)
- $\text{arr}(k)$ = arrival node (i.e., TLOF pad) for aircraft type k
- $\text{dest}(k)$ = destination node for aircraft type k
- $I_j^k(t)$ = external inflow of aircraft of type k into node j at time t
- $c^d(k)$ = benefit of an aircraft of type k departing per unit time
- $c^a(k)$ = benefit of an aircraft of type k arriving per unit time
- $x_{i,j}^k(t)$ = (decision variable) number of flights of type k that depart from TOLA node i at time t and arrive at node j at time $t+t_{i,j}$

Equations 1 through 6 describe the general IP formulation for TOLA operations used in this analysis. A verbal description is provided above each equation.

Objective Function: Maximize the total value awarded for aircraft arrivals and departures.

$$maximize \left(\sum_{\{k,t,i=dest(k)\}} c^d x_{i,j}^k(t) + \sum_{\{k,t,i=arr(k)\}} c^a x_{i,j}^k(t) \right) \quad \text{(Eqn. 1)}$$

Flow Conservation Constraint: for each commodity, the flow into each node plus the external inflow at the node equals the flow out of the node.

$$\sum_{\{j:(i,j)\in N(k)\}} x_{i,j}^k(t) - \sum_{\{j:(j,i)\in N(k)\}} x_{j,i}^k\left(t - t_{j,i}\right) + I_j^k(t) = 0 \;\; \forall S,k,t \quad \text{(Eqn. 2)}$$

TLOF Conflict Constraint: only one aircraft can be on the approach, taxi-in, taxi-out, and/or departure arcs associated with a TLOF node at a time. This constraint varies depending upon the TLOF pad operating variable in effect. The constraint presented below is for fully dependent operations at a TLOF pad. This constraint is repeated for each TLOF pad in the model.

$$\sum_k \sum_{\{t':t-t_{i,j}<t'\leq t\}} \left(\sum_{\{i:(i,pad1arr)\in N(k)\}} x_{i,pad1arr}^k\left(t'\right) + \sum_{\{j:(pad1arr,j)\in N(k)\}} x_{pad1arr,j}^k\left(t'\right) + \sum_{\{i:(i,pad1dep)\in N(k)\}} x_{i,pad1dep}^k(t') + \sum_{\{j:(pad1dep,j)\in N(k)\}} x_{pad1dep,j}^k(t') \right) \leq 1 \quad \forall t,i \quad \text{(Eqn. 3)}$$

Gate Conflict Constraint: only one aircraft can be on the taxi-in, taxi-out, staging taxi-in/out, turnaround, and/or hold arcs for each gate node at a time. This constraint varies depending upon the taxiway operating variable in effect. The constraint presented below is for unidirectional taxiway operations. This constraint is repeated for each gate in the model.

$$\sum_k \sum_{\{t':t-t_{i,j}<t'\leq t\}} \left(\sum_{\{i:(i,gate1arr)\in N(k)\}} x_{i,gate1arr}^k\left(t'\right) + \sum_{\{j:(gate1arr,j)\in N(k)\}} x_{gate1arr,j}^k\left(t'\right) + \sum_{\{i:(i,gate1rdy)\in N(k)\}} x_{i,gate1rdy}^k(t') + \sum_{\{j:(gate1rdy,j)\in N(k)\}} x_{gate1rdy,j}^k(t') \right) \leq 1 \quad \forall t,i \quad \text{(Eqn. 4)}$$

Arc Capacity Constraint: the sum of the flow of all aircraft commodities on each arc must be less than or equal to the capacity of that arc.

$$\sum_k \sum_{\{j:(i,j)\in N(k)\}} \sum_{\{t':t-t_{i,j}<t'\leq t\}} x_{i,j}^k(t') \leq C_i(t) \;\; \forall t,i \quad \text{(Eqn. 5)}$$

Positive Integer Constraint: decision variables must be non-negative and integer.

$$x_{i,j}^k(t) \geq 0,\; integer \;\; \forall i,j,k,t \quad \text{(Eqn. 6)}$$

The IP formulation was implemented in Python 3.6.6. using Gurobi 8.0.1 as the solver. A different flow model was developed for each TOLA architecture considered.

A TOLA architecture consisted of a specified number of gates, TLOF pads, and staging stands. Furthermore, each TOLA architecture was solved for multiple sets of operational variables that manipulated the travel time and TLOF pad/taxiway operating constraints for each arc. In this manner the potential design space for TOLAs was sampled over the range of values in Table 13. For the initial tradespace analysis it was assumed each TLOF pad was connected to all gates through a taxiway; therefore, the taxiway layout infrastructure variable does not appear in the range of sampled values in Table 13.

Table 13 Independent variables for the TOLA throughput capacity analysis

	Independent Variable	**Tested Value**
Infrastructure Variables	Number of TLOF Pads	1 to 3
	Number of Gates	1 to 12
	Number of Staging Stands	0 to 9
Operational Variables	Aircraft Turnaround Time (s)	30 to 600
	Inter-Arrival Time (s)	15 to 90
	Inter-Departure Time (s)	15 to 90
	Gate Taxi-Time (s)	5 to 90
	Staging Stand Taxi-Time (s)	5 to 90
	Independent TLOF Pads	yes, no, or paired
	Independent Taxiways	yes or no

In total, the IP was formulated for 160 different TOLA architectures in the tradespace analysis. Each was solved for up to 146 different operational variable combinations. The tradespace analysis used throughput capacity as the objective and consisted of the development of approximately 9000 capacity envelopes representing the solution of the IP 220,000 times. The solutions of maximum throughput capacity were calculated for a 15-minute operating period.

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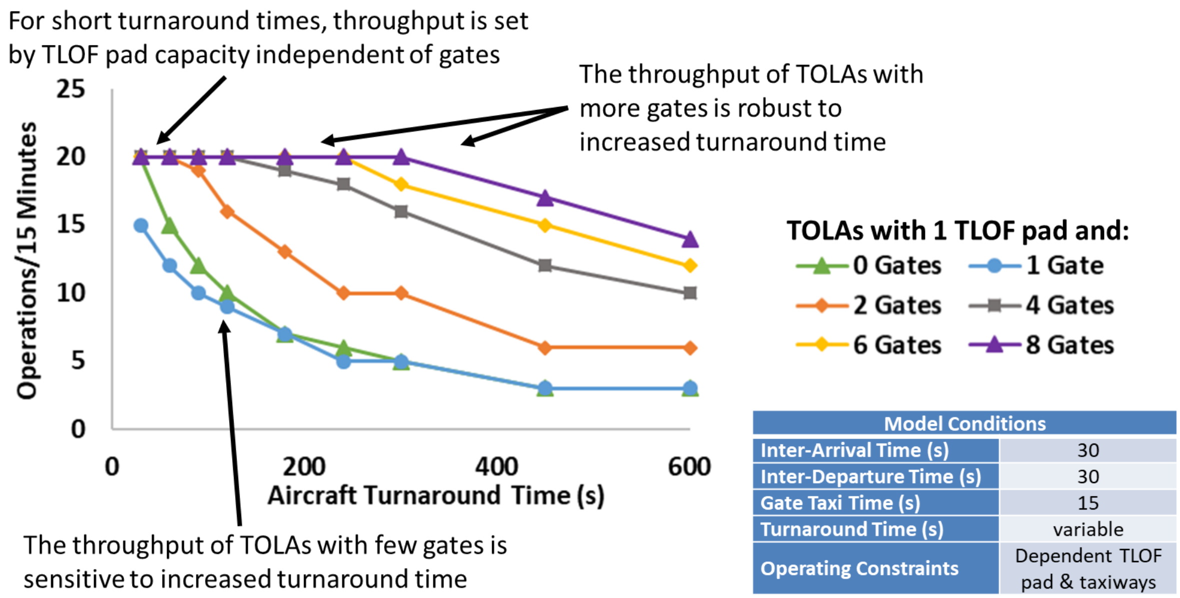
5.3.2 Sensitivity of Throughput Capacity to Aircraft Turnaround Time

TOLA throughput capacity was found to be dependent upon aircraft turnaround time as a function of the ratio of gates to TLOF pads at the TOLA.

Fig. 24 presents the maximum deterministic throughput capacity of six TOLAs as a function of aircraft turnaround time. Each TOLA has one TLOF pad and between zero and eight gates. The data presented in Fig. 24 are for a 30 s inter-arrival time, 30 s inter-departure time, and 15 s taxi time with unidirectional (i.e., dependent) taxiway operations. For perspective, turnaround times of 60 s to 180 s were demonstrated for 30-passsenger helicopters by the helicopter airlines when refueling was not required [12] while turnaround times on the order of 600 s are anticipated for fully-electric aircraft to allow for charging [5].



Model Conditions	
Inter-Arrival Time (s)	30
Inter-Departure Time (s)	30
Gate Taxi Time (s)	15
Turnaround Time (s)	variable
Operating Constraints	Dependent TLOF pad & taxiways

Fig. 24 Maximum deterministic throughput capacity for six TOLAs with varying numbers of gates as a function of aircraft turnaround time.

In Fig. 24, an increase in turnaround time leads to an immediate reduction of throughput capacity for TOLAs with few gates and a gradual reduction for TOLAs with more gates. In other words, TOLAs with a higher gate to TLOF pad ratio are more robust to increased aircraft turnaround time.

The TOLAs with a higher gate to TLOF pad ratio are more robust to long turnaround time because multiple aircraft may simultaneously be turned at the TOLA (one per gate). Robustness to turnaround time may be important for UAM logistics as extended onboard safety briefings, longer than expected charging times, or passengers who need more time may stochastically increase aircraft turnaround time compared to the design condition.

Additional gate capacity may provide no throughput benefit when turnaround times are short. In Fig. 24 the TOLA without a gate provides the same throughput as the TOLA with eight gates when turnaround time is 30 s. The maximum throughput is capped at 20 operations in 15 minutes for all TOLAs due to the TLOF pad capacity. The TOLA with one gate supports a lower throughput than the TOLA without a gate due to the additional taxi time required for an aircraft to reach the gate before it could be turned (as opposed to being turned directly on the TLOF pad).

While additional gates will not increase maximum throughput when the TLOF pad capacity is reached, the addition of independent TLOF pads enables a TOLA to increase throughput capacity as displayed in Fig. 25. The tradeoff between higher gate to TLOF pad ratios and additional independent TLOF pads in terms of throughput per footprint is explored in Section 5.4.

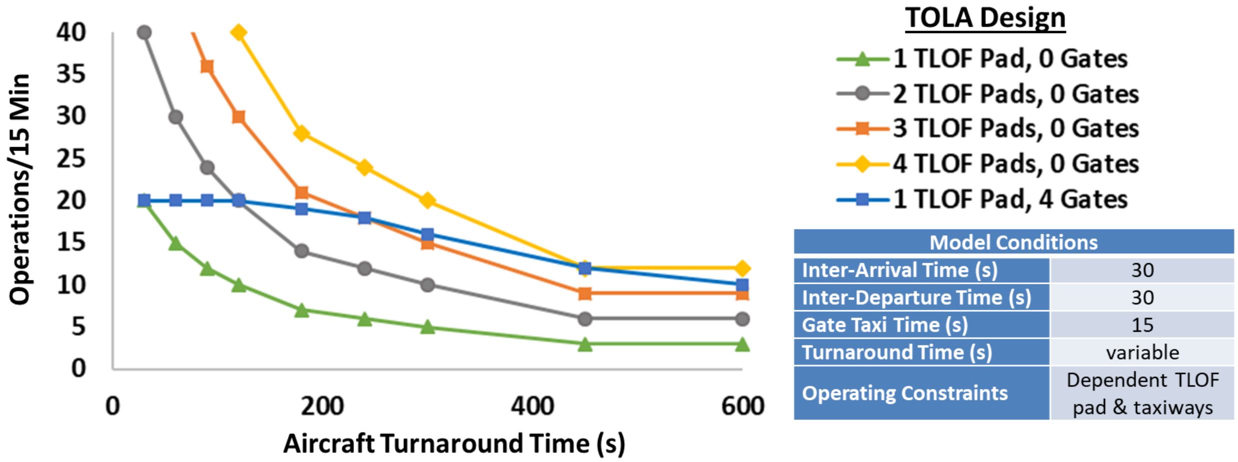


Fig. 25 Maximum deterministic throughput capacity for five TOLAs with a varying number of TLOF pads and gates as a function of aircraft turnaround time.

5.3.3 Sensitivity of Throughput Capacity to Aircraft Inter-Arrival Time

The data presented in Fig. 24 were produced for a constant inter-arrival and inter-departure time of 30 s. If inter-arrival time is increased to 90 s, then the maximum throughput for TOLAs with any number of gates is reduced for all aircraft turnaround times as displayed in Fig. 26. For short turn-times, the TLOF pad capacity limits throughput more severely than for long turn-times (12 operations in Fig. 26 compared to 20 operations in Fig. 24). Increasing inter-departure time has a similar impact on TOLA throughput but is not shown in this section.

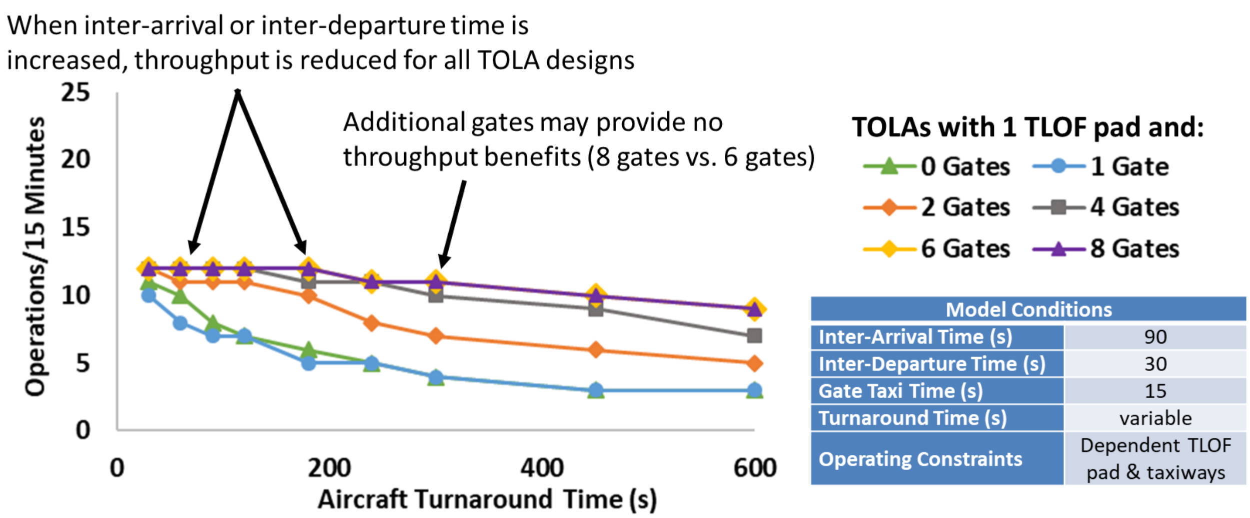


Fig. 26 Maximum deterministic throughput capacity for six TOLAs as a function of aircraft turnaround time with a long inter-arrival time.

In Fig. 26, the eight-gate TOLA does not provide any throughput benefits compared to the six-gate TOLA for any aircraft turnaround time shown. This is in comparison to the increased throughput that the seventh and eighth gates provided with a shorter inter-arrival time in Fig. 24.

This trend is more clearly shown in Fig. 27 which displays TOLA throughput as a function of inter-arrival time with constant 30 s inter-departure and 300 s turnaround times. TOLAs with many gates have significant throughput benefits when inter-arrival time is small compared to turnaround time. However, these TOLAs experience a rapid decline in throughput with increasing inter-arrival time as the TLOF pad becomes congested and the extra gates are starved for aircraft.

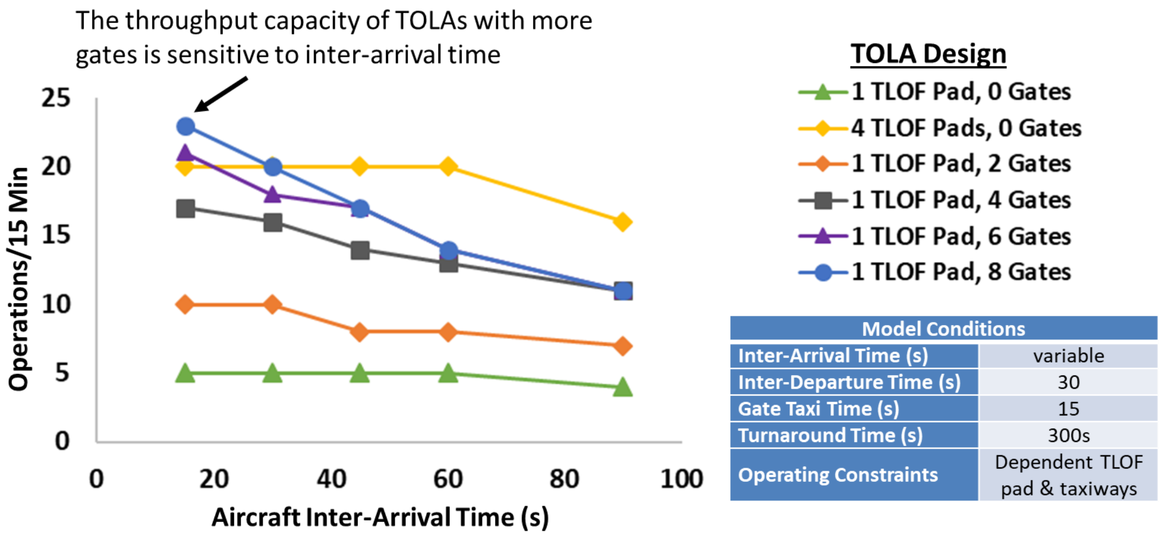


Fig. 27 Maximum deterministic throughput capacity for six TOLAs as a function of inter-arrival time.

This sensitivity of throughput to inter-arrival time is interesting from a design and operations perspective because it is opposite the trend seen for aircraft turnaround time. While additional gates add resilience against variation in turnaround time, the throughput benefits of additional gates reduce with increased inter-arrival time. For perspective, VFR inter-arrival times of 15 s to 30 s have been demonstrated by GA aircraft at the EAA AirVenture Oshkosh Airshow and helicopters at Silverstone racetrack during the British Grand Prix. IFR inter-arrival times are generally on the order of minutes due to larger separation requirements.

5.3.4 Sensitivity of Throughput Capacity to Aircraft Taxi Time

If a TOLA is developed such that only one aircraft can taxi to or from the gate(s) at a time, then an increased taxi time results in reduced throughput capacity irrespective of the number of gates. In this case, taxi time effectively increases the inter-arrival time of the aircraft as aircraft that have completed their turn may be forced to wait at the gate before taxiing out. If simultaneous taxiing is allowed (such as through bidirectional taxiway design), then increased taxi time has a small effect on optimal gate to TLOF pad ratio as displayed in Fig. 28.

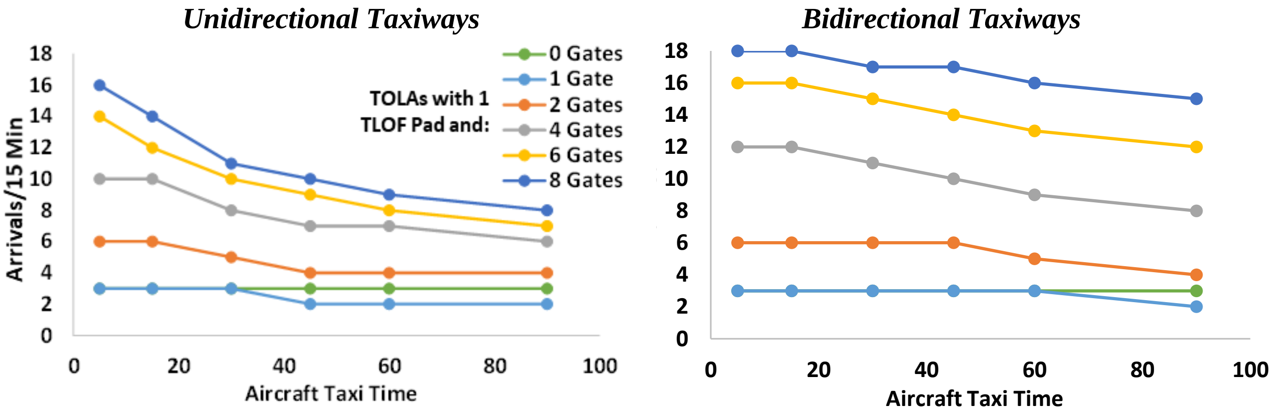
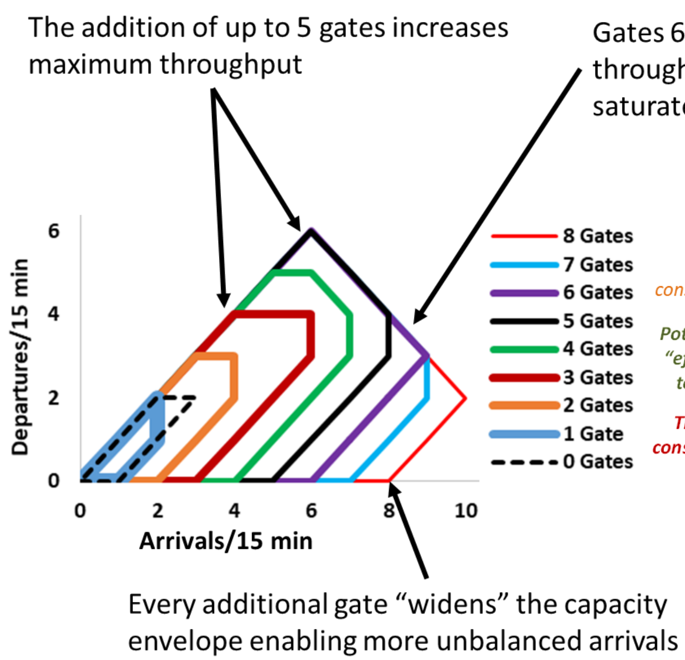


Fig. 28 Sensitivity of TOLA arrival capacity to one-way vs two-way aircraft flow on taxiways.
Results for 30 s inter-arrival time, 30 s inter-departure time, and 300 s turnaround time.

5.3.5 Impact of Gate to TLOF Pad Ratio on a TOLA's Capacity Envelope

Fig. 29 displays nine capacity envelopes that correspond to TOLAs with one TLOF pad and zero to eight gates. The utilization of each TLOF pad and gate is displayed in the table on the right in Fig. 29. The operational variables for this example were set to a 60 s inter-arrival and inter-departure times, a 15 s taxi time, and a 300 s aircraft turnaround time.



	Vertiport Topology	TLOF Pad Utilization	Avg. Gate Utilization	Avg. Gate Holding
Gate constrained	0 Gates	33%	67%	0%
	1 Gate	33%	73%	0%
	2 Gates	58%	61%	0%
Potentially "efficient" topology	3 Gates	83%	64%	6%
	4 Gates	90%	43%	0%
	5 Gates	98%	46%	5%
TLOF pad constrained	6 Gates	98%	46%	11%
	7 Gates	98%	50%	16%
	8 Gates	98%	38%	12%

Model Conditions	
Inter-Arrival Time (s)	60
Inter-Departure Time (s)	60
Gate Taxi Time (s)	15
Turnaround Time (s)	300
Operating Constraints	Dependent TLOF pad & taxiways

Fig. 29 Capacity envelopes and component utilizations for TOLAs with increasing gate to TLOF pad ratios.

In Fig. 29, adding the first gate reduces the maximum throughput of the TOLA compared to the TOLA without a gate by preventing a third arrival from occurring. This effect is the result of the taxi time required to access the gate compared to turning the aircraft directly on the TLOF pad. This impact would have been minimized if taxi operations could have simultaneously occurred in both directions on the taxiway to or from the gate as shown in Fig. 28.

Adding two to five gates increases a TOLA's throughput capacity and the TLOF pad utilization (for this specific set of operational variables). The additional gates allow more aircraft to conduct their turnaround in parallel.

When a sixth gate is added, however, the maximum throughput (i.e., number of arrivals plus number of departures) no longer increases. As may be seen in the utilization table on the right of Fig. 29, the TLOF pad utilization reached 98% with the addition of the fifth gate and it may no longer support additional operations even if more aircraft could be turned by the gates. Although additional gates beyond this "balanced" ratio do not increase the maximum throughput, they provide the ability to handle additional unbalanced operations (displayed as extra arrivals in the capacity envelopes of Fig. 29).

Importantly, the addition of the second and third gates generated a greater marginal increase in maximum throughput capacity than adding the fourth or fifth gates. This was caused by sequencing inefficiencies in arrivals and departures for more tightly scheduled operations. When TLOF pad utilization is low, the taxiways and TLOF pad could generally accommodate a departure as soon as the aircraft was prepared to depart the gate. However, as the TOLA approached the balanced gate ratio there was less slack in the operations and aircraft more frequently experienced ground holding at the gates or airborne holding before arriving. Therefore, in some cases it may be more efficient from a throughput perceptive to add additional independent TLOF pads instead of additional gates even when below the balanced gate to TLOF pad ratio.

5.3.6 Sensitivity of Throughput Capacity to Staging Stands and Pre-Staged Aircraft

Fig. 30 displays the effect of adding up to eight staging stands to a TOLA with one TLOF pad and four gates. Each staging stand that is added supports one additional "unbalanced" arrival. An unbalanced arrival is an arrival that does not correspond with a departure during the study period (15 minutes in this case). Unbalanced arrivals appear as a widening of the capacity envelope. This trend continues until the TLOF pad supports only arrivals (not shown in this diagram, but the point when the maximum throughput line intersects the x-axis).

If the TLOF pad is not fully saturated (i.e., 100% utilization), then an additional staging stand may also increase the total number of operations (arrivals plus departures) that may be conducted. This condition occurs in Fig. 30 between the 0 and 1 stand scenarios, and again between the 1 and 2 stand scenarios.

Fig. 31 displays the effect of adding pre-staged aircraft to a TOLA with one TLOF pad, two gates, and two staging stands. Pre-staged aircraft were vehicles that were located at the gates or staging stands prior to the

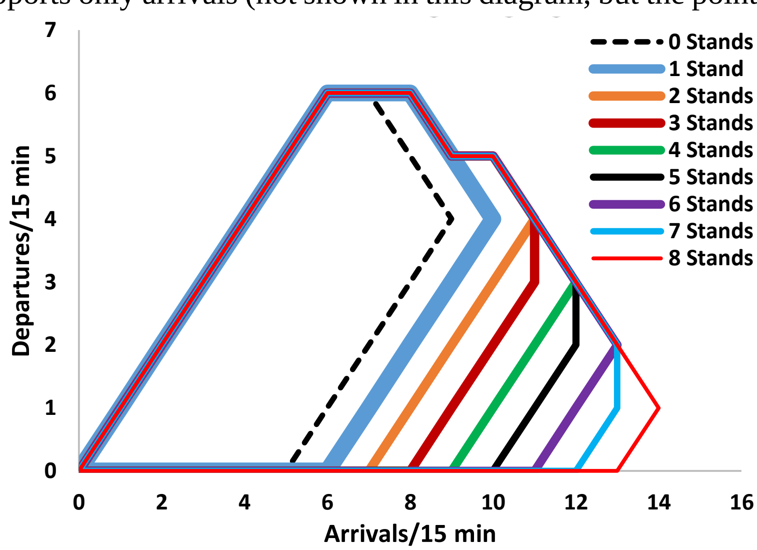


Fig. 30 Effect of adding staging stands to a TOLA with one TLOF pad and four gates. *Results for 60 s inter-arrival time, 60 s inter-departure time, 300 s turnaround time, and bidirectional taxiways.*

solution of the IP. Aircraft pre-staged at the gates were assumed to already have completed their turnaround.

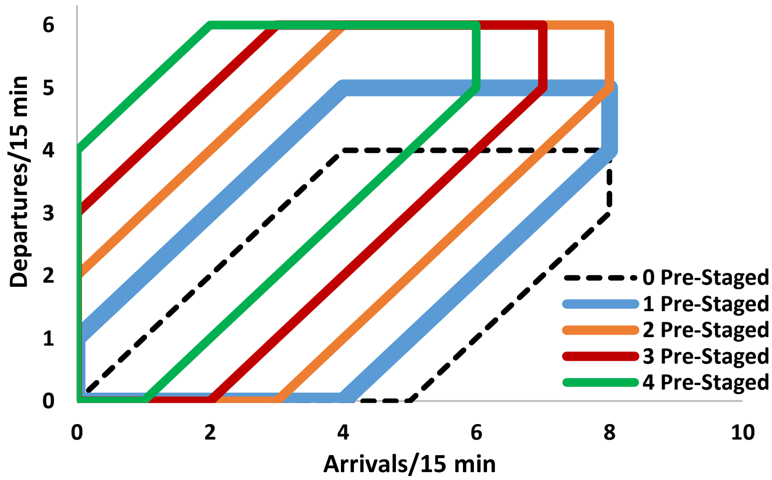


Fig. 31 Effect of adding pre-staged aircraft to a TOLA with one TLOF pad, two gates, and two staging stands. *Results for 60 s inter-arrival time, 60 s inter-departure time, 300 s turnaround time, and bidirectional taxiways.*

The first two pre-staged aircraft added to the TOLA shift the entire capacity envelope vertically upwards. This signifies that one additional departure and one fewer arrival may be supported due to each pre-staged aircraft *except* for in the maximum arrival case. The maximum number of arrivals remains the same (8 arrivals) for all three capacity envelopes. For this set of conditions, the first two pre-staged aircraft therefore increase the maximum throughput capacity of the TOLA. Additional pre-staged aircraft beyond the initial two reduce the maximum throughput capacity as the pre-staged aircraft must depart before new arrivals can be accepted and begin their turnaround process. The additional pre-staged aircraft do continue to increase the number of unbalanced departures that may be supported

As displayed in Fig. 30 and Fig. 31, the number of staging stands and pre-staged aircraft may play a significant role in the throughput potential of a TOLA by increasing the number of unbalanced operations that may occur. (Note this is also a feature of adding additional gates). The ability to support unbalanced arrivals or departures may be critical for TOLA operations during morning or evening commuting hours or during airline flight banking periods where UAM traffic may be highly directional.

5.3.7 Sensitivity of Throughput Capacity to Independent TLOF Pad Operations

In order to increase the throughput capacity of a TOLA beyond what a single TLOF pad may support, additional TLOF pads may be added. However, these additional TLOF pads will not increase throughput unless they support simultaneous operations with the other TLOF pads at the TOLA (or at a nearby TOLA). The level of independence between TLOF pads is a function of lateral separation minima and aircraft equipage as discussed in detail in Chapter 7. Three different TLOF pad independence scenarios were evaluated in the tradespace analysis and are introduced below.

<u>*Independent Operations*</u>

The most effective scenario to maximize multi-TLOF pad throughput is to enable fully independent operations where arrivals or departures can occur at one pad without relation to what is occurring at any other pad. If independent TLOF pads do not share gates, then the facility operates as two separate TOLAs and double the throughput. If the TLOF pads share gates, then the throughput of the TOLA may more than double due to marginal efficiency gains in gate usage under some circumstances.

Furthermore, connecting multiple independent TLOF pads to the same set of gates increases the robustness of throughput performance to fluctuations in inter-arrival, inter-departure, and taxi time. If an aircraft were to become disabled on a TLOF pad, taxiway, or gate, such a configuration also provides greater flexibility for off-nominal operations. Finally, connected TLOF pads may simplify ground operations by enabling one-way taxiing from one TLOF pad that exclusively accepts arrivals to the second that exclusively supports departures.

Dependent Operations

Adding a fully dependent TLOF pad to a TOLA provides no throughput capacity benefit unless unidirectional taxiways are in use. In that case, a second dependent TLOF pad may increase throughput by streamlining taxi operations and preventing inefficiencies due to reverse taxiing on one taxiway. Dependent TLOF pads therefore provide few throughput capacity benefits to TOLAs, but they may provide robustness and operational benefits.

Paired, Dependent Operations

If adjacent TLOF pads may support paired arriving flights or paired departing flights, the throughput of a TOLA may match that of independent TLOF pads. The primary advantage of paired arrivals and departures is they may enable the spacing of TLOF pads closer than the typical 200 ft required for independent VFR operations or the multiple thousands of feet required for simultaneous IFR operations. This opportunity is discussed in further detail in Chapter 7.

5.3.8 Summary of Throughput Capacity Sensitivities to TOLA Design and Operations

Based on the findings of the tradespace analysis, the key implications of the TOLA infrastructure and operational variables are summarized as:

- The number of independent TLOF pads and the number of gates associated with each TLOF pad are the principal TOLA design drivers of deterministic throughput capacity.
- When aircraft turnaround time is long relative to both inter-arrival and inter-departure time, then the deterministic throughput capacity of a TOLA is maximized either by increasing the number of gates associated with each TLOF pad or by increasing the number of TLOF pads that may support simultaneous independent or paired aircraft operations.
- When aircraft turnaround time is short relative to both inter-arrival or inter-departure time, then the number of TLOF pads that may support simultaneous independent or paired aircraft operations is the most significant driver of TOLA throughput.
- A large number of gates per TLOF pad increases the robustness of throughput capacity to increased turnaround time; however, the throughput capacity of TLOF pads with many gates rapidly diminishes with increased inter-arrival time.
- Each gate or staging stand supports an additional unbalanced arrival or departure (i.e., an arrival without a corresponding departure or vice-versa) which enhances the TOLA’s capability to support periods of directional flight demand (such as during banking periods or commuting rush hours).

5.4 Example Estimation of Throughput for Footprint-Constrained TOLAs

The methods developed in the previous two sections were combined to estimate the throughput of example TOLAs constrained to a footprint of 500 ft or less in their longest dimension. Previous research demonstrated TOLA infrastructure of less than 500 ft significantly increases the number of potentially viable sites in major cities [41,67,90,102].

The results identify promising TOLA topologies to maximize throughput capacity for a given footprint and operating condition, display how operating conditions influence throughput, and provide an order of magnitude estimate for feasible UAM throughput at a TOLA.

5.4.1 Approach

Two example cases were considered with footprints representative of an inner-city TOLA location:

1. a rooftop with an available physical footprint of 300 ft by 300 ft, and
2. a waterway or highway with an available physical footprint of 500 ft by 200 ft.

For each case, TLOF pads, gates, and taxiways were arranged within the available footprint according to the satellite, pier, and linear topologies. Next, the deterministic throughput capacity for the TOLA architecture was estimated using the IP model from Section 5.3. Potential throughput was estimated in five operating conditions described in Table 14. All five operating conditions assumed aircraft surface operations on unidirectional taxiways (i.e., no passing on a taxiway).

Table 14 Operating conditions for example TOLA analysis.

Notional Scenario	Turnaround Time (s)	Inter-Arrival Time (s)	Inter-Departure Time (s)	Taxi Time (s)	Spacing between Independent TLOF pads (ft)
VFR – Short Turn	60	30	30	15	200
VFR – Medium Turn	300	30	30	15	200
VFR – Long Turn	600	30	30	15	200
IFR – Short Turn	60	90	30	15	700
IFR – Medium Turn	300	90	30	15	700

The VFR, short turn scenario represented operating conditions similar to those demonstrated by helicopter airlines [12] and charter helicopter services. The VFR, medium turn scenario represented proposals by Uber that provide time for the fast charging of electric aircraft [70]. The VFR, long turn scenario was a more conservative estimation of aircraft charging time.

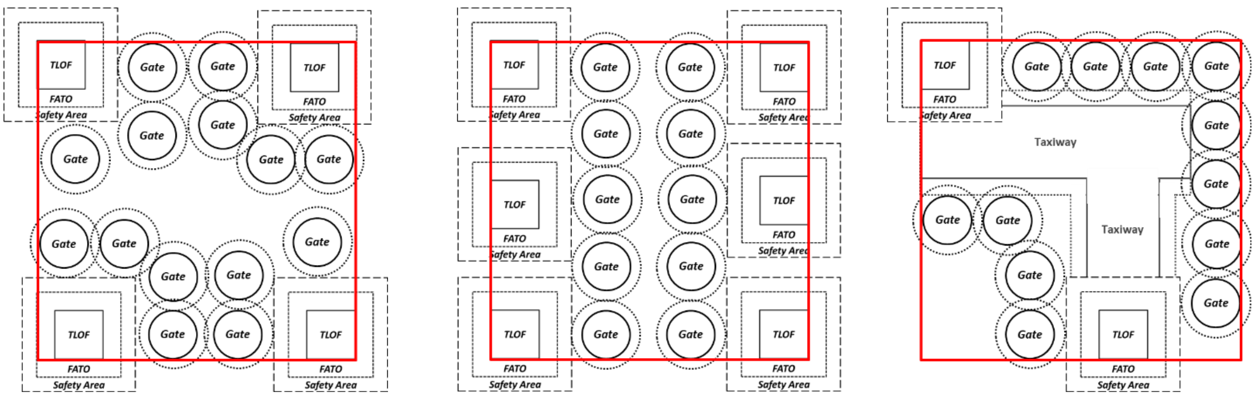
In the IFR scenarios, the inter-arrival time and independent TLOF pad spacing were both increased to account for larger separation minima. It may be noted that the minimum TLOF pad spacing for simultaneous and independent IFR aircraft operations is 700 ft [108] which was larger than the example TOLA footprints considered. Different inter-departure times were not considered because diverging departure trajectories may support IFR departures similar to in visual conditions [108].

The objective of these studies was to maximize aircraft throughput capacity for each footprint. Consideration was therefore not given to passenger access or egress, maintenance and servicing operations, or terminal integration. These additional considerations may make a specific topology more desirable for actual implementation even if it does not maximize throughput capacity.

Furthermore, the throughput data developed were for deterministic operations and were intended as an upper bound estimate of potential TOLA performance. Achievable throughput would be less than these estimations on average due to stochasticity in the operations and the need to build slack into the schedule to prevent cascading delays.

5.4.2 300 ft by 300 ft Footprint Case Study

The three TOLA architectures in Fig. 32 display layouts that maximize the number of gates and TLOF pads that may be located within a 300 ft by 300 ft physical footprint for the satellite, linear, and pier topologies. Table 15 displays the maximum deterministic throughput of each TOLA architecture in the five operating scenarios from Table 14.



Satellite Topology *Linear Topology* *Pier Topology*

Fig. 32 Potential topologies for a TOLA with a 300 ft by 300 ft physical footprint.

Table 15 Fifteen-minute deterministic throughput for TOLA topologies with a 300 ft by 300 ft footprint.

		Operational Scenario				
		VFR: 30s inter-arrival			IFR: 90s inter-arrival	
TOLA Design		60s turn	300s turn	600s turn	60s turn	300s turn
Satellite Topology	4 TLOF pads 14 gates	60 arr 60 dep	42 arr 28 dep	28 arr 14 dep	7 arr 7 dep	8 arr 6 dep
Linear Topology	6 TLOF pads 10 gates	62 arr 56 dep	30 arr 20 dep	10 arr 5 dep	7 arr 7 dep	8 arr 6 dep
Pier Topology	2 TLOF pads 12 gates	30 arr 30 dep	30 arr 20 dep	18 arr 12 dep	7 arr 7 dep	8 arr 6 dep

For a 300 ft by 300 ft footprint, the satellite topology strictly dominated the pier topology from a throughput capacity standpoint. The width of the taxiway in the pier topology limited the number of gates and TLOF pads that could be supported on the limited footprint; this in turn reduced the throughput potential TOLAs with the pier topology.

When inter-arrival time and turnaround time are both short, topologies that maximize the number of independent TLOF pads enable the highest throughput independent of the number of gates. The satellite and linear topologies both support four independent TLOF pads; the two middle TLOF pads in the linear topology supported only dependent operations. However, for longer turnaround times of 300 s or 600 s the throughput of the liner topology was more rapidly reduced than the satellite topologies as it had fewer gates at which to conduct aircraft turnaround. Considering these factors, the satellite topology maximizes VFR throughput for this available footprint.

Beyond throughput, the three topologies in Fig. 32 result in different potential challenges for ATC. To utilize the four independent TLOF pads in the satellite or linear topologies, aircraft must arrive and depart at the TOLA with converging angles to one another. The pier topology, on the other hand, may support aircraft flow in one direction with one TOLA handling arrivals and the other handling departures.

Finally, under IFR conditions each topology is restricted to the use of only one TLOF pad at a time due to lateral separation minima. Instrument conditions therefore represent a significant scaling constraint for TOLA infrastructure. Chapter 7 will discuss possible means to support IFR arrivals and departures on TLOF pads spaced more closely than 700 ft as a means to increase TOLA throughput capacity.

5.4.3 500 ft by 200 ft Footprint Case Study

Many potential urban locations for UAM TOLAs have thin and long footprints including highways, railways, or waterways. The TOLA architectures in Fig. 33 display potential TOLA designs with a 500 ft by 200 ft physical footprint for the three topologies. Table 16 displays the maximum, deterministic throughput of each TOLA in five operating scenarios.

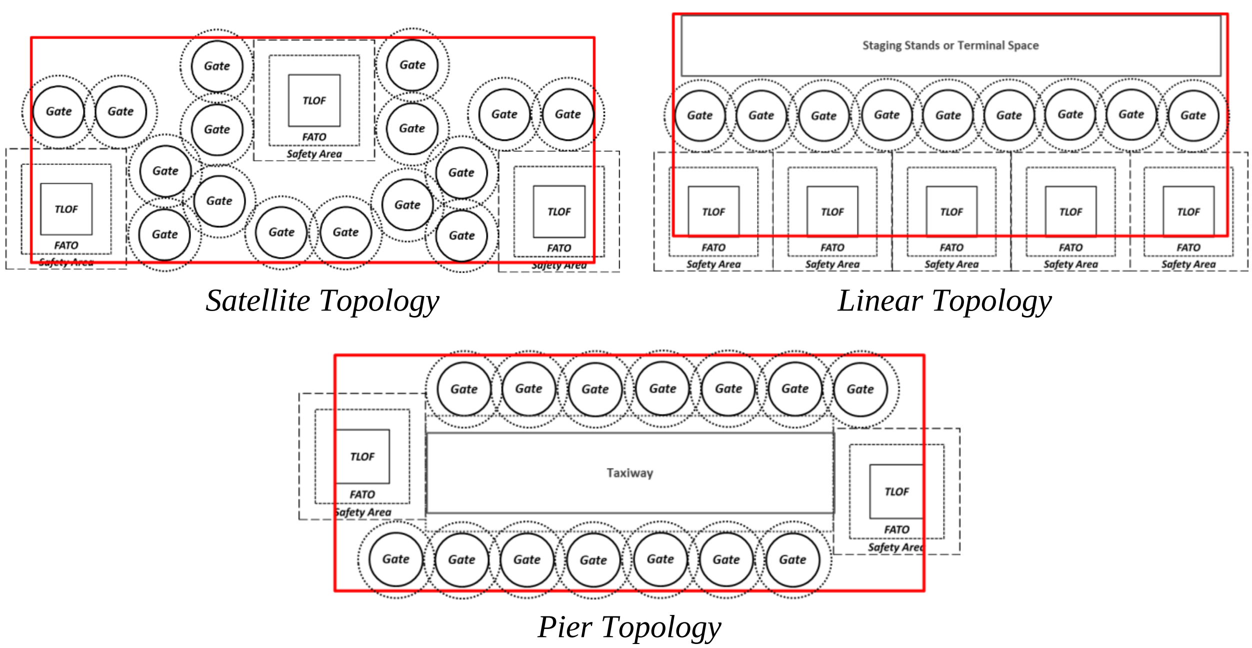


Fig. 33 Potential topologies for a TOLA with a 500 ft by 200 ft physical footprint.

Table 16 Fifteen-minute deterministic throughput for TOLA topologies with a 500 ft by 200 ft footprint.

TOLA Design		Operational Scenario				
		VFR: 30s inter-arrival			IFR: 90s inter-arrival	
		60s turn	300s turn	600s turn	60s turn	300s turn
Satellite Topology	3 TLOF pads 16 gates	45 arr 45 dep	39 arr 28 dep	25 arr 16 dep	7 arr 7 dep	8 arr 6 dep
Linear Topology	5 TLOF pads 9 gates	46 arr 43 dep	27 arr 18 dep	18 arr 9 dep	7 arr 7 dep	8 arr 6 dep
Pier Topology	2 TLOF pads 14 gates	30 arr 30 dep	30 arr 22 dep	18 arr 14 dep	7 arr 7 dep	8 arr 6 dep

Similar to the previous case, the pier topology was unable to efficiently utilize the available footprint and was strictly dominated by the satellite topology in terms of throughput capacity for all operating scenarios.

When turn-time is short, the additional gates of the satellite topology were not utilized and the linear topology provided comparable throughput capacity. However as turn-time increased, additional gates are necessary to maintain throughput. The two dependent TLOF pads in the linear topology do not provide increased throughput capacity for the linear topology. The space used by those pads would support higher throughput if converted to gates.

5.5 Conclusion

The findings from this chapter discuss the impacts of TOLA design and operating conditions on aircraft throughput capacity, footprint requirements, and operational robustness to off-nominal conditions. Due to limited siting opportunities for TOLAs within dense, urban areas, TOLAs with a small physical footprint that may support a high volume of aircraft operations are a direct enabler of UAM scaling.

The key design variables that set TOLA throughput and footprint are the number of TLOF pads developed at the facility that support simultaneous and independent UAM flights and the number of gates associated with each TLOF pad. The number of pads or gates required to maximize throughput for a given footprint was shown to be primarily dependent upon three operational variables, namely the inter-arrival time of aircraft, turnaround time of aircraft, and required lateral separation between independent TLOF pads.

When UAM aircraft operate under visual flight rules (VFR), inter-arrival time and TLOF pad lateral separation requirements are small. With conservative estimates for turnaround time on the order of ten minutes, a UAM TOLA with a footprint of 300 ft by 300 ft could potentially support on the order of 100 aircraft operations per hour. A reduction of turnaround time (primarily a function of aircraft design, TOLA infrastructure, and passenger management) could increase throughput to the order of 500 operations per hour.

However, when UAM operate under instrument flight rules (IFR) the existing lateral separation minima may preclude the development of independent TLOF pads at TOLAs with footprints less than multiple thousands of feet. Furthermore, inter-arrival time is significantly increased compared to VFR operations due to longitudinal separation requirements. As a result, the maximum IFR throughput for a TOLA is reduced to approximately 50 operations per hour. IFR operations therefore represent the most critical scenario where TOLA throughput may constrain UAM scale. Aircraft inter-arrival time and TLOF pad independence are primarily attributes of ATC and are further investigated in the next chapters.

Future work should explore the robustness of TOLA operations to realistic variance in operational parameters and off-nominal conditions. The deterministic formulation of the IP in this chapter estimates upper-bound throughput capacity, but does not represent practical throughput considering stochastic aircraft performance. Furthermore, tightly scheduled deterministic solutions are susceptible to stability issues. The development of stochastic simulation capabilities for capacity envelopes would be valuable to expand the findings of this chapter. Finally, this chapter did not consider the potential for three dimensional, stacked TOLA concepts, or the integration of terminal infrastructure and passenger access to the gates. These are areas for future research.

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6 Air Traffic Control Services for UAM

This chapter takes a functional look at ATC to determine what attributes of the service may constrain the feasible scale of UAM operations.

UAM missions are anticipated to frequently be impacted by ATC. For example, 94% of the reference missions presented in the exploratory case studies of Chapter 4 had an origin or destination TOLA located within controlled airspace. Further, the analysis of TOLA operations in Chapter 5 determined that ATC-prescribed separation minima were a principle determinant of TOLA throughput, especially under IFR. UAM scaling may be impacted if access to TOLAs is delayed by ATC or if flight times are lengthened due to diversions around controlled airspace.

6.1 Approach

The influence of ATC on UAM scaling is presented as an airspace capacity problem. With this framing, the scale of UAM operations at a TOLA or between TOLAs is constrained when the overlying airspace is no longer able to support additional flights. Separation minima, controller workload, and airspace structure are proposed as the critical components of ATC that will limit the feasible scale of UAM operations based upon a review of prior literature.

Properties of these three components of ATC are introduced with a focus on how they may influence UAM scaling. Potential approaches (technical and operational) to increase airspace capacity by relieving one or more of the ATC components are reviewed. Example current-day implementations of these strategies to enable high-volume, VFR operations are discussed.

The development of segregated airspace where UAM operations are procedurally separated from conventional flights and do not require ATC services is proposed as a promising near-term approach to relieve UAM scaling restrictions due to ATC.

The analysis in this chapter assumed that conventional aircraft operations could not be adjusted to accommodate UAM flights. In particular, large commercial aircraft were assumed to remain on procedures similar to those with which they currently operate for safety, cost, and political reasons.

6.2 UAM Scaling Dependence on Airspace Capacity

This thesis defines the scale of a UAM network as the number of passenger or cargo trips that can occur within a specified geographic region in a reference time period. ATC influences UAM scale by controlling the number of aircraft that may enter or exit the airspace overlaying the geographic region of interest. "Airspace capacity" was therefore adopted as a metric with which to evaluate the scaling impact of ATC on UAM.

The capacity of airspace is defined by Krozel et al. [110] as "the maximum number of aircraft per unit time that can be safety accommodated by the airspace, given controller and pilot workload constraints and airspace constraints (e.g., special use airspace, convective weather constraints, etc.)." Majumdar and Ochieng [111] similarly define airspace capacity as "the maximum number of aircraft that are controlled in a particular ATC sector in a specified period, while still permitting an acceptable level of controller workload."

Based upon these definitions, airspace capacity is time dependent. Both definitions focus on the measurement of capacity over a specific time period as opposed to an instantaneous measurement. This suggests the number of aircraft ATC may support in an airspace may fluctuate around a time-averaged capacity limit, such as may be the case during banking periods or coordinated UAM arrivals and departures.

Majumdar and Ochieng also define capacity in terms of a "sector." A sector is a volume of airspace with designated lateral and vertical boundaries, typically managed by a single controller or team of controllers. The manner into which airspace is divided into sectors (or other units) influences airspace capacity for UAM operations.

Furthermore, both definitions of airspace capacity indicate that there are a variety of factors in addition to the geometry (i.e., sectorization) of airspace that influence capacity. Controller workload arises in both definitions, and Krozel et al. further mention pilot workload, weather, and special use airspace (SUA) as factors that influence airspace capacity. Functional decomposition of ATC services by Shin et al. at Perdue University [112] suggests separation minima and traffic sequencing as additional factors influencing for airspace capacity. Finally, Metron Aviation [113] also proposed procedure design and communication, navigation, and surveillance (CNS) capabilities as factors influencing airspace capacity.

The variation of these factors between metropolitan areas results in different airspace capacities and UAM scaling potential. Fig. 34 displays the author's model for how each of the airspace capacity factors proposed by these studies relate to airspace capacity.

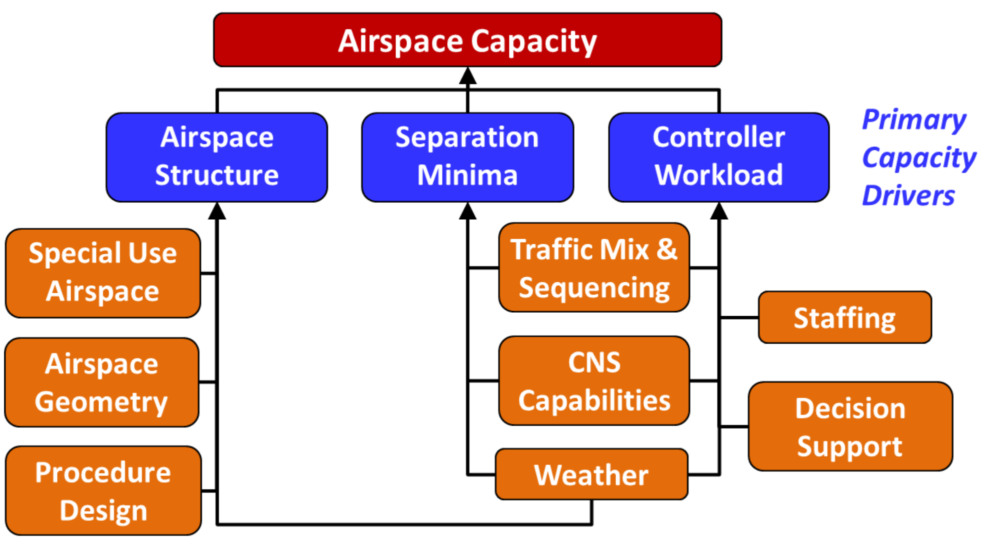

Fig. 34 Key factors of ATC that influence airspace capacity.

The three factors indicated in blue in Fig. 34 were perceived to directly influence airspace capacity; these factors were called "capacity drivers." Alternatively, the factors indicated in orange were components of the drivers that impact airspace capacity through one or more of the drivers.

Special use airspace, airspace geometry, procedure design, and weather jointly define the structure of an airspace where UAM may operate. The presence of an active SUA in an area may require flight diversions for UAM aircraft or special entry requirements and equipage. The geometry of an airspace, including the lateral and vertical extent of controlled airspace, obstructions from terrain or obstacles, and shape of sectors influence where ATC services are provided and how aircraft may operate in the airspace. Procedure design determines the organization of routes and traffic flows within an airspace, and weather influences how sectorization is conducted and the procedures that may be utilized.

Weather conditions also determine the separation minima between aircraft and impact controller workload. When weather conditions require UAM to operate under IFR, separation minima are increased. Controller workload is increased for IFR operations when radar separation must be provided.

CNS capabilities and the mix of traffic also affect airspace capacity through the separation minima and controller workload drivers. For example, advanced CNS enables aircraft to operate more closely to other aircraft and/or communicate more efficiently with controllers. Similarly, a heterogenous traffic mix reduces airspace capacity because larger wake vortex separation may be required between aircraft of different masses.

Increased controller staffing and/or the use of decision support tools may enhance controller capabilities to support a higher volume of aircraft operations in an airspace by preventing the workload of any one controller from reaching a saturation point.

The three capacity drivers represent the primary mechanisms through which ATC services may constrain the scale of UAM operations. Each driver is briefly summarized below and discussed in depth in the following sections.

1. *Separation Minima*: In terminal airspace, controllers typically must provide a specific distance, time, or height between an aircraft and all other aircraft or obstacles. Longitudinal separation influences the inter-arrival time for aircraft at TOLAs and the throughput rate for flight routes. Lateral separation limits the spacing between independent TLOF pads or flight routes. Vertical separation influences the how closely UAM aircraft may operate to the surface as well as the design of flight routes and their crossing points. In general, larger separation requirements reduce airspace capacity compared to smaller requirements
2. *Controller Workload*: ATC is currently a voice-based, human-centric activity where controller workload is proportional to traffic volume, airspace complexity, and communications requirements, among other factors [114–116]. If a controller’s workload is high they may delay UAM access or egress in controlled airspace by prescribing airborne or ground holding, or by withholding a clearance or not responding to a pilot’s request.
3. *Airspace Structure*: For VFR operations, controller workload and ATC-applied separation minima impact UAM scaling only within terminal-controlled airspace. The geometry of terminal airspace, as well as SUA that may restrict UAM flight, is therefore influential on where ATC may limit UAM scaling. Regions where these airspace volumes are fewer or smaller are expected to exhibited reduced ATC scaling for VFR UAM services. For UAM operations within these airspace volumes or under IFR, the design of flight routes and procedures impact the number of aircraft that may operate and diversions required compared to the haversine distance.

6.3 Separation Minima

Separation minima limit how closely aircraft may operate to one another or obstacles. Separation minima constrain UAM scaling by limiting the density of flights in an airspace and/or the throughput of TOLAs (due to inter-arrival spacing and independent TLOF pad spacing).

Aircraft separation standards are derived from the need to:

1. prevent aircraft conflicts with other aircraft or obstacles, and
2. prevent wake vortex encounters (i.e., flight through air disturbed by a previous aircraft).

Considering these goals, the amount of separation required in a given situation is dependent upon the type (i.e., class) of airspace an aircraft is flying in, the mass of the aircraft, the CNS systems of the aircraft and controllers, the weather conditions, and the aircraft's configuration (i.e., helicopter, fixed-wing, or other).

6.3.1 Variation of Separation Minima Type of with Airspace, Aircraft, and Operation

Fig. 35 displays the six classes of airspace used in the U.S. national airspace system. Class A airspace exists at high altitudes and is not relevant for UAM. Class B and C airspace exist at major airports with significant commercial or military traffic. Class D airspace typically surrounds GA airports with few or no commercial passenger services. Surface-level class B, C, and D airspace is typically managed by on-site controllers in a control tower. Low traffic airports with or without a control tower may be surrounded by Class E airspace. Class G airspace is uncontrolled and is not managed by ATC.

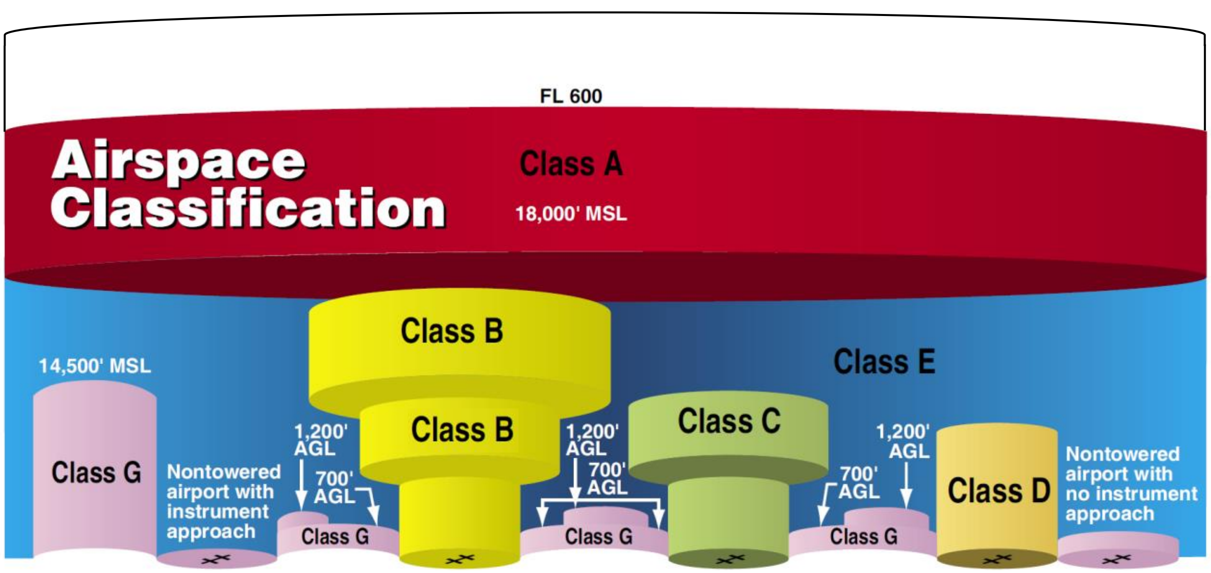

Fig. 35 Airspace structure of the U.S. national airspace system.
Image adapted from the FAA *Pilot's Handbook of Aeronautical Knowledge* [117].

Table 17 summarizes the airspace classes where air traffic controllers must provide separation between aircraft. When there is no requirement for controllers to provide separation, aircraft pilots are responsible for their own separation.

Table 17 Summary of air traffic controller separation responsibilities.

Aircraft Type and Flight Rule for Separation	*Controller Separation Responsibility by Airspace Class*				
	B*	C*	D*	E	G
all IFR aircraft ⇔ all IFR aircraft	y	y	y	y	
all IFR aircraft⇔ all SVFR aircraft	y	y	y	y	
all SVFR aircraft ⇔ all SVFR aircraft	y	y	y	y	
IFR fixed-wing ⇔ all VFR aircraft	y	y			
VFR fixed-wing ⇔ all VFR aircraft	y				
IFR helicopter ⇔ VFR fixed-wing	y				
IFR helicopter ⇔ VFR helicopter					
VFR helicopter ⇔ VFR helicopter					

VFR: Visual Flight Rules SVFR: Special Visual Flight Rules IFR: Instrument Flight Rules
**ATC clearance or communication required to enter airspace*

The first three rows of Table 17 indicate that all aircraft must be separated from one another by controllers when operating under IFR or special VFR (SVFR) in any controlled airspace. For VFR operations, however, controllers must only provide separation in class B or C airspace.

In class B airspace around major airports, controllers must ensure separation between all aircraft except between a helicopter operating under VFR and any other helicopter. This difference of separation requirements based on aircraft configuration may enable UAM aircraft that are considered to be helicopters to leverage smaller separation minim in class B airspace. Controllers are not required to separate any two VFR flights (helicopter or fixed-wing) in either class C or D airspace. They also may not be required to separate VFR operations from IFR flights in class D airspace.

6.3.2 Separation Requirements

Separation is generally fulfilled in one of three ways:

1. Radar Separation: air traffic controllers actively manage separation of aircraft using radar tracking and voice communications.
2. Non-Radar Separation: air traffic controllers passively manage separation by assigning aircraft to non-interfering routes or airspace sterilized of other aircraft.
3. Visual Separation: separation is provided either by a tower controller having sight of both aircraft and communication with at least one, or by the pilot of one aircraft accepting self-separation responsibility from other aircraft in the vicinity.

Fig. 36 presents the relationship between the various separation minima that are frequently utilized in terminal airspace. The type of separation required and its size are dependent upon the weather conditions, the classification of the aircraft (helicopter vs. fixed-wing) or operator (Part 91 vs Part

135), and the CNS capabilities of the aircraft and controller. The primary requirements for applying each type of separation are listed in Fig. 36 and described in greater depth in Table 18.

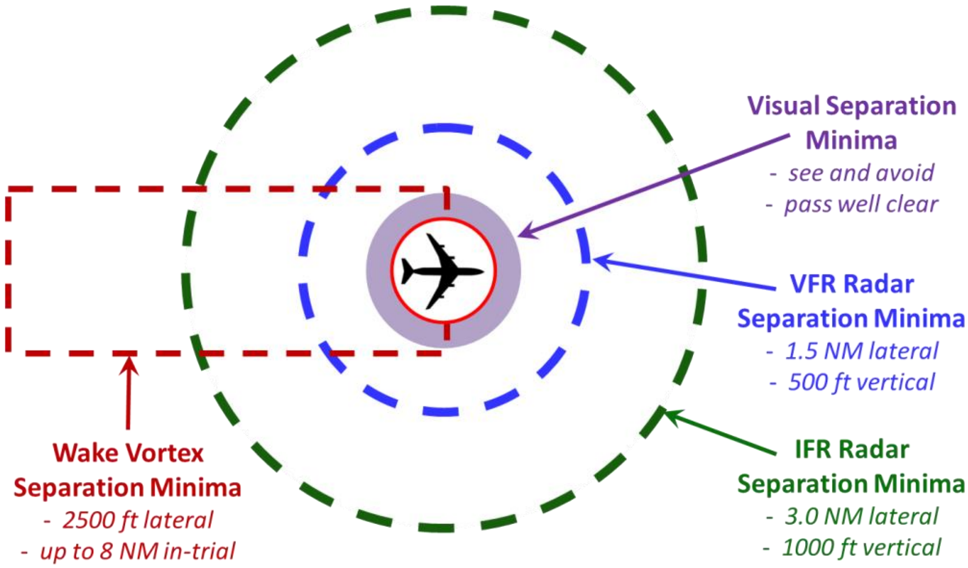

Fig. 36 Separation standards that may apply to terminal-area UAM operations.

Table 18. Summary of ATC separation requirements for terminal area operations.

Aircraft Involved	Lateral Separation Requirement	Vertical Separation Requirement	Longitudinal Separation Req.
IFR to IFR	3 NM	1000 ft	up to 8 NM
IFR to VFR	radar target resolution, 1.5 NM, or visual separation	500 ft or visual separation	up to 8 NM
VFR to VFR			
SVFR to IFR/SVFR *fixed-wing aircraft*	≥ 4 NM (non-radar) or visual separation	500 ft or visual separation	≥ 5 NM or visual separation
SVFR to IFR/SVFR *helicopters*	½ - 1 NM or visual separation	500 ft or visual separation	up to 8 NM

Visual separation requirements for pilots are specified in Title 14 of the Code of Federal Regulations (CFR) Part 91.113. To maintain visual separation a pilot must "see and avoid" and "pass well clear" of other aircraft during flight. Controllers may also apply visual separation as specified in Joint Order 7110.65 section 7-2-1. Unlike each other separation standard, no numerical value is specified for the minimum lateral, vertical, or longitudinal distance for visual separation; it is up to the pilot or controller to assess appropriate visual separation minima.

VFR radar separation generally requires 1.5 NM laterally or 500 ft vertically between aircraft in terminal areas. If enabled by their radar display equipment and settings, controllers may use radar target resolution to provide VFR lateral radar separation of less than 1.5 NM. VFR radar separation in class B airspace for fixed-wing aircraft may be applied in weather conditions where aircraft have visibility of at least three miles and can remain clear of clouds. Part 135 helicopters, however, only require visibility of ½ mile in the day or one mile at night in order to operate with VFR radar separation. IFR radar separation may be applied in any weather and requires 3.0 NM laterally or 1000 ft vertically for all aircraft types.

Special VFR enables the use of visual separation or reduced radar separation when visibility is below the VFR weather minima. However, SFVR is not authorized for Part 135 operators or for fixed-wing aircraft at most major airports. Non-radar separation uses time-based or heading-based methods to ensure aircraft separation, and wake-vortex separation requires a specific distance or time between some aircraft on crossing or coincident courses.

Although not pictured in Fig. 36, commercial aircraft with more than 30 seats are also required to equip with a Traffic Collision Avoidance System (TCAS) that provides an implicit minimum separation requirement in any operating condition. UAM aircraft may or may not be required to equip with TCAS; however, if UAM operations must not interfere with commercial aircraft then it is assumed they should not trigger a TCAS resolution advisory for commercial aircraft on approach or departure from airports.

TCAS tactically prevents mid-air collisions by alerting the pilot to situations where an intruder aircraft will simultaneously violate a minimum horizontal and vertical separation requirement within a given time horizon. The TCAS separation minima vary with altitude and closure speed; however, the minimum separation is 600 ft vertically and approximately a third of a nautical mile laterally for flights occurring below 5000 ft. TCAS alerts are suppressed for aircraft targets operating below 360 ft above ground level (AGL) enabling UAM aircraft to operate within these minima if remaining below this altitude [118].

6.3.3 Reducing the Impact of Separation Minima on UAM Scaling

Larger separation minima are more likely to constrain UAM scaling, especially in urban areas or near TOLAs where aircraft must operate in relatively close proximity to one another. Previous work by NASA suggested that IFR radar separation standards could limit the number of simultaneous UAM operation over the city of San Francisco to two or three aircraft [33].

Reducing the impact of separation on UAM scaling may be achieved by minimizing the separation minima applied in a given flight scenario. As introduced in the two previous sections, there are a number of existing operational and technological opportunities that UAM operators may leverage to minimize separation requirements without the need for new technologies or rulemaking.

For example, UAM operations that exclusively occur under VFR or SVFR may leverage reduced radar separation requirements as well as apply visual separation in most scenarios. The application of visual separation, in particular, significantly reduces the impact of separation on UAM scaling as there are no quantitative minima for visual separation. While the use of VFR and SVFR are limited by weather conditions, UAM operations that adopt vehicles considered by ATC as helicopters benefit from reduced visibility minima enabling the use of VFR separation minima in more scenarios. Chapter 8 further discusses differences in visual separation use by helicopters and fixed-wing aircraft.

UAM operations may also minimize the magnitude of separation minima applied by operating outside controlled airspace or airspace classes with more stringent separation requirements. UAM routes that avoid class B and C airspace do not require ATC to provide separation between large airliners and VFR UAM flights. Furthermore, UAM routes that do not enter class B airspace do not require ATC to provide separation between a VFR UAM flight and any other VFR operation. UAM route and trajectory design may reduce the impact of separation minima on service scaling simply by avoiding these airspace types.

UAM pilots may also take advantage of smaller wake vortex separation requirements by limiting scenarios where they follow larger aircraft. Constrained position shifting (CPS) is an example of a technique to manage airport arrival sequencing with the objective of maximizing airspace and runway capacity [119].

While the previous examples concerned operational techniques through which UAM flights may leverage reduced separation minima, UAM operators may also leverage a number of emerging technologies to reduce separation requirements for specific operations. For example, advanced CNS technologies including vehicle to vehicle communication technologies, pilot automation, and new obstacle sensing capabilities may enable aircraft to operate with reduced separation minima in instrument conditions [33].

Similarly, the implementation of performance based navigation (PBN) for UAM may enable more closely spaced routes or routes in closer proximity to traditional airport procedures [120]. More specifically, the PBN required navigation performance (RNP) technology relies upon satellite-based navigation, ground-based or satellite-based augmentation systems, and onboard performance monitoring and alerting to provide the high degree of operational integrity required to reduce separation minima [121]. The most advanced RNP procedures currently support IFR separation from obstacles by as little as 0.2 NM [122] as compared to the current 3.0 NM IFR radar separation requirements.

6.4 Controller Workload

UAM aircraft cannot operate in class B, C, or D airspace without first communicating with a controller. Controllers primarily communicate with pilots through the use of very high frequency (VHF) radios where a single controller uses one radio frequency. UAM access to TOLAs or flight routes within these airspace volumes may therefore be constrained either if a controller is too busy to support additional flights (i.e., their workload is saturated) or if the radio frequency is too congested for the pilot to effectively communicate with the controller (i.e., radio frequency congestion).

Air traffic control towers respond to controller workload or radio frequency saturation by:

1. delaying or excluding flights in controlled airspace (i.e., reducing traffic volume),
2. increasing the number of controllers and independent radio frequencies to maintain an acceptable service to traffic ratio, and/or
3. reducing controller workload and radio communications dedicated to each aircraft.

The first action above addresses workload or frequency saturation by adjusting traffic demand in an airspace. More specifically, controllers implement a variety of traffic management initiatives (TMIs) to reduce the number of aircraft entering an airspace to an acceptable workload level. TMIs include assigning ground or airborne holding, diverting aircraft around the saturated airspace, or precluding specific operations or aircraft from entering the airspace. Beyond directly reducing UAM system throughput in a controlled airspace, a TMI may also reduce the time savings of the UAM mission compared to the alternative transportation modality resulting in a reduction of customer demand.

Alternatively, the second and third actions by ATC seek to address workload or frequency saturation by adjusting the capacity of the ATC system. The following two sections provide an estimate for the number of flights controllers may currently support and introduce potential capacity adjustment opportunities to support UAM.

6.4.1 Staffing to Traffic Ratio and UAM Scaling Through Increased Staffing

The FAA does not use an explicit, quantitative method to specify the number of aircraft a single controller may support in a given period [123]. Rather, controllers reach workload saturation when their cognitive load exceeds their personal comfort level to provide the required ATC services. Similarly, the number of aircraft operations a radio frequency may support in a given period is not a fixed number, but rather is a function of the number of transmissions per aircraft, the length of the transmissions, and the sequencing of the transmissions (i.e., spread out over time or occurring concurrently).

Major airports may operate with a single local controller up to a throughput on the order of 20 flights per hour (including flights arrivals, departures, and transits). To increase throughput further, towers open additional controller positions and subdivide airspace, traffic, and responsibilities among the new controllers (and their radio frequencies). In 1960, both Midway and O'Hare airports supported roughly 135 helicopter operations per day through a dedicated helicopter controller position [69]. The BOS ATC tower currently opens a separate controller position when there are approximately three or more simultaneous helicopter or GA operations in its airspace.[9]

Providing a similar estimate, initial human in the loop experiments simulated for Dallas-Fort Worth International Airport by NASA suggest that a local controller may be able to support between five and ten simultaneous UAM operations alongside their conventional traffic load in visual conditions [97]. For ATC services at airports that primarily support GA flights (these airports were assumed to more closely resemble UAM TOLAs than commercial airports), teams

[9] Based on interviews with the Boston Logan Airport Tower Manager

of two controllers may support between 80 and 120 VFR operations per hour for fixed-wing aircraft, and a single controller may be capable of upwards of 100 VFR helicopter operations per hour.[10]

In instrument meteorological conditions (IMC), however, staffing to traffic ratios are reduced. Two to three controllers may support on the order of 50 large aircraft operations per hour to an independent runway.[11] Furthermore, if IFR arrivals occur to runways that do not meet the minimum lateral separation requirements for independent operations, then up to four controllers may be required to manage arrivals to two runways due to additional workload requirements for trajectory conformance monitoring [108].

Controller workload is different for en-route operations than for arrivals and departures. The monitor alert parameter (MAP) is used by the FAA to estimate the number of aircraft a controller may simultaneously manage in en-route airspace. The MAP therefore provides an initial impression of UAM traffic to staffing ratios for transiting flights near airports (as opposed to arrival and departure operations).

The MAP assumes a controller dedicates an average of 36 seconds of attention to each flight [98]. This indicates that if the average UAM flight time in a controller's airspace is five minutes, then a controller may support on the order of ten simultaneous transits if tasking is assumed to be sequential. TOLA throughput projections on the order of dozens of operations in 15 minutes from Chapter 5 would therefore exceed the current capabilities of a single controller.

While increased controller staffing has historically provided relief to scaling limitations from workload and radio communications, there are diminishing returns for each new controller in terms of aircraft throughput. Subdividing airspace into smaller and smaller volumes increases the complexity of the airspace, reduces the amount of time a controller manages a given flights, and increases the number of transitions of aircraft between controllers and radio frequencies. These factors, among others, reduce the number of aircraft a controller may handle within their airspace of responsibility. As a result, achieving a scale of UAM flights that is an order of magnitude beyond current controller capabilities may not be achievable only through an order of magnitude increase in staffing, but may also require a reduction of the amount of time a controller must dedicate to an individual flight.

6.4.2 Reducing Controller Workload Per Flight

A primary source of controller workload is communication with the aircraft. On average, controllers spend close to 30% of their time conveying routine clearances and information to pilots [116]; in terminal areas this may be as large as 50% [97]. Minimizing voice communication requirements is therefore an effective means to reduce controller workload per flight. Other mechanisms to reduce controller workload per flight include developing standard flow patterns, using data-link communications, and enabling pilots to self-separate visually.

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[10] Based on interviews with two GA airport controllers

[11] Conventional, single-runway IFR throughput based on San Diego International Airport capacity profile. Retrieved 7/31/2019 from www.faa.gov/airports/planning_capacity/profiles/

The development of standard flow patterns such as visual procedures at airports and VFR routes within controlled airspace reduce communications by implicitly communicating numerous waypoint commands in the procedure assignment. These routes follow distinct surface features such as roads or rivers and may be navigated quite precisely as shown through radar tracking analysis of helicopter and small aircraft in Appendix B.

Furthermore, data-link communications provide an alternative to radio communications for clearance delivery that may limit radio frequency saturation. The development of simplified verbal clearances was also shown by NASA as a means to increase traffic to staffing ratios [97]. Reduced communications strategies such as these are demonstrated each year at the EAA AirVenture Oshkosh airshow and the Silverstone heliport at the British Grand Prix where each event supports multiple hundreds of GA operations to a single TOLA each hour.

Providing separation is another major source of controller workload, especially for IFR flights. The degree of workload from providing separation is dependent upon the complexity of the traffic situation [114,115,124]. For example, IFR arrival procedures may have multiple merge points, turns, and handoffs between different controllers. Each of these attributes increases the complexity of the airspace, traffic, and operation [114]. Simultaneous IFR arrivals are an especially challenging separation scenario and may require the addition of two or more “monitoring” controllers dedicated solely to this task.

There are a variety of strategies to reduce controller workload resulting from IFR or VFR separation services.

First, procedure and runway layout may be simplified to reduce controller workload. Developing routes with greater lateral or vertical separation, fewer merging or crossing points, and straight-in arrivals reduces the complexity of air traffic and minimizes areas where a potential loss of separation may occur. Runways or TLOF pads with greater centerline separation may also reduce arrival and departure procedure complexity and the associated staffing and workload requirements.

Second, the responsibility for separation may be distributed from the controllers to pilots or automation. Controllers may authorize pilots to maintain visual separation under VFR or SVFR. Furthermore, advanced CNS systems like PBN may enable procedures such as established on RNP (EoR) that reduce controller workload by transferring separation responsibility from controllers to the aircraft’s automation and flight crew. As another example, the NASA Unmanned Aircraft System Traffic Management (UTM) and Air Traffic Management eXploration (ATM-X) projects are developing new airspace management tools for controllers and automated ATC systems [125].

Third, controllers may be relieved from the responsibility to provide separation in specific airspace or between certain aircraft. For example, controllers are not required to provide separation between VFR helicopters in class B airspace, or between any VFR aircraft and other VFR or IFR aircraft in class D airspace. Similarly, UAM operations may maximize their operations outside the terminal airspace boundaries or inside a special flight rules area (SFRA) where controllers are not required to provide separation. SFRAs over the Los Angeles International Airport and the Hudson River in New York currently support dozens to hundreds of daily VFR flights without controller interaction or services.

6.5 Airspace Structure

Airspace structure concerns the definition of airspace geometry and the organization of aircraft flow patterns within it. Sections 6.3 and 6.4 introduced how UAM route design (an aspect of airspace structure) that avoids entry into class B, C, or D controlled airspace could reduce ATC constraints on UAM scaling resulting from separation and controller workload. This section introduces further components of airspace structure and their influence on UAM operations.

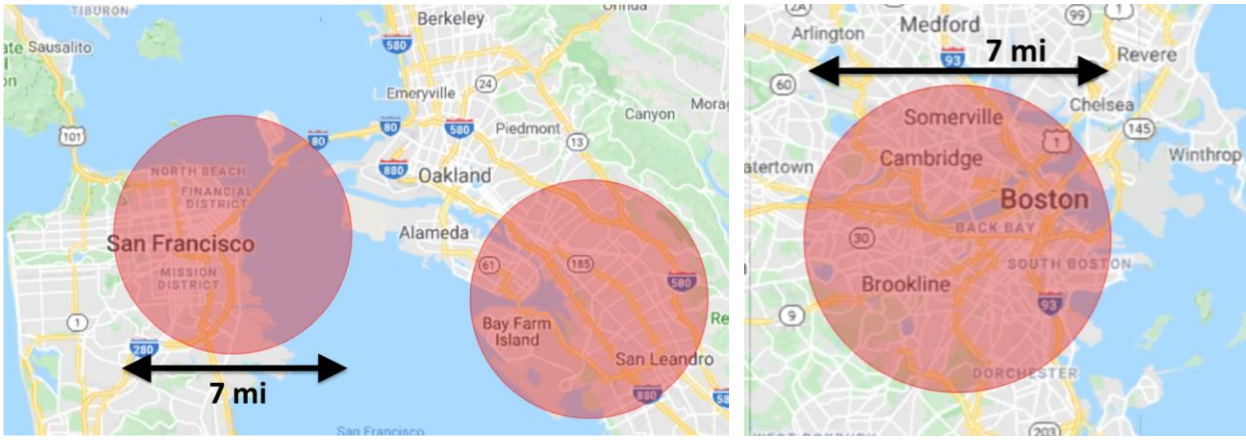
6.5.1 Special Use Airspace (SUA)

Special use airspace is an additional type of airspace that can limit UAM throughput or access. Furthermore, due to the low altitudes at which UAM aircraft will operate compared to conventional commercial aircraft, the influence of SUA on airspace structure is likely to be more profound due to the increased frequency of SUA near the surface.

UAM operations can be excluded from SUA permanently, intermittently, or optionally depending upon the type of SUA:

- Prohibited Airspace: airspace typically surrounding a security sensitive area that UAM aircraft are never authorized to enter.
- Restricted Airspace: airspace typically surrounding a military area that UAM may enter when it is either not active or when they are given explicit clearance by ATC.
- Temporary Flight Restriction (TFR): airspace that is either permanently or intermittently active in which UAM aircraft may be excluded from entering for security or flight safety purposes. The most common TFR is defined around large sports stadiums during events. In order to enter stadium TFRs, UAM must receive explicit clearance by ATC.
- Military Operating Areas, Warning Areas, and Alert Areas: airspace in which hazards to flight may exist. UAM aircraft may enter these areas at their own risk, potentially with additional limitations or information provided through a Notice to Airman (NOTAM).
- Special Conservation Areas: the Aeronautics Information Manual (AIM) requests pilots to maintain a minimum altitude of 2000 ft above U.S. parks, wildlife refuges, and forest service areas. Although not a regulatory requirement in the AIM, some conservation areas such as the Grand Canyon and Yosemite national parks prohibit flight below 2000 ft through specific public laws. Furthermore, frequent UAM flight below 2000 ft in these areas, even if technically permitted, may have a higher probability of triggering community acceptance issues.

Each of these types of SUA were identified in 34 large metropolitan areas in the U.S. as a first-order assessment of how frequently they may influence UAM operations. TFRs for sports stadiums were present in nearly every metropolitan area, often directly within the city centers. As an example, Fig. 37 displays TFRs for baseball stadiums in San Francisco, Oakland, and Boston, that may impact UAM flight in substantial proportions of each city’s downtown area up to approximately 80 days a year.



San Francisco and Oakland *Boston*

Fig. 37 Temporary flight restrictions at baseball stadiums that may restrict UAM flights.
Image © Google, 2019.

Special conservation areas were located within a number of cities in the western U.S., but the other SUAs were infrequently located in populated regions. The one exception, however, was the restricted airspace that overlays Washington, DC. The DC restricted area prohibits all aircraft operations within approximately 15 miles of the city center except for flights specifically authorized by the FAA and vetted by the Transportation Security Administration (TSA).

Considering these findings, SUA, especially for sporting events, represent additional airspace volumes where UAM scale may be limited by ATC.

6.5.2 Airspace Geometry

The geometry (location, shape, and size) of controlled airspace and SUA is set by ATC policy with adjustments made for local conditions. TFRs for sporting events are generally three nautical miles in radius and span from the surface up to 3000 ft AGL. Class B, C, and D controlled airspace have standard dimensions, but are frequently adjusted to contain the IFR approach and departure procedures for the airport(s) they contain or to accommodate traffic from neighboring airports.

The geometry of controlled airspace is especially critical for airspace capacity as VFR operations are only subject to controller workload limits or radar separation minima when operating within a terminal-controlled airspace. As a result, terminal airspace geometries that reduce the size of controlled airspace can increase UAM operating scale by releasing airspace where operations are unrestricted by ATC.

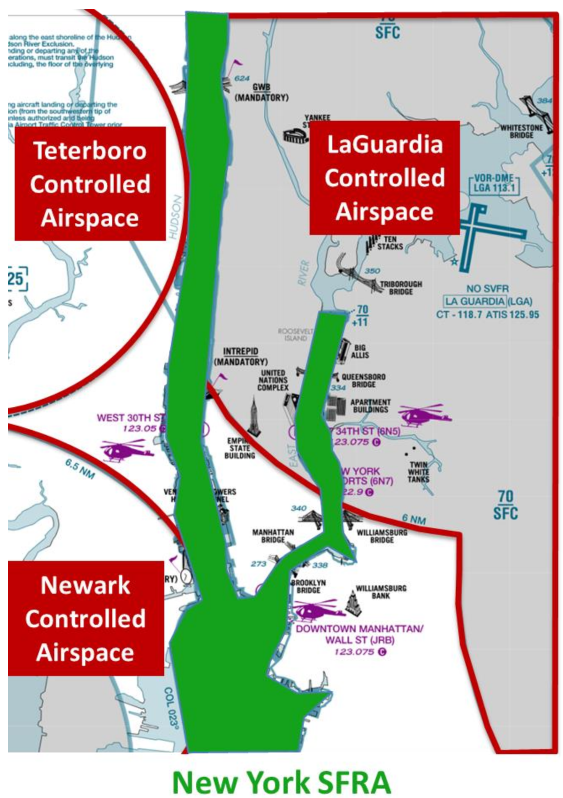
The FAA historically leveraged airspace geometry in three ways to increase airspace capacity for small aircraft and GA operations. The three approaches include reducing the shape or size of controlled airspace, designating areas within controlled airspace to be managed with special flight rules, and designating areas within controlled airspace to be managed by a third-party airspace service provider. These three approaches provide insight into opportunities to increase the scaling potential of UAM and are briefly discussed below.

First, the FAA Metroplex Project redesigned a number of Class B areas in part to increase their volume efficiency and release previously controlled airspace for uncontrolled VFR operations [126]. The San Francisco Class B airspace redesign in 2018 is an example of this process. Approximately five miles of controlled airspace west of the airport (indicated in red in Fig. 38) was released through the newly defined surface-level controlled airspace (colored green). However, despite the potential benefits of a full airspace redesign, the timeline and costs associated with the redesign process may limit its applicability to enable near-term UAM scaling.

Fig. 38 Redesigned San Francisco class B airspace (green) compared to prior airspace (red) displaying reduction of controlled volume.
Image © Google, 2019.

A second airspace geometry approach historically used to increase airspace capacity for small aircraft operations is the development of special flight rules areas (SFRAs). SFRAs are volumes of airspace that are "cut out" from the surrounding controlled airspace. Flights within the SFRA are procedurally segregated from conventional airport traffic. The SFRA is considered to be uncontrolled airspace and is not provided ATC services. Pilots are also not required to communicate with controllers.

Fig. 39 displays the extent of the SFRA over the Hudson river in New York City. Helicopters and aircraft operating within the SFRA are not subject to ATC and do not have communicate with controllers. The New York SFRA previously supported over 60,000 VFR sightseeing helicopter operations per year, plus many additional thousands of GA and charter flights. These operations occur through pilot self-separation and without ATC services.



Airspace cutouts such as the New York SFRA do not require a ground-up redesign of the entire controlled airspace, but rather the identification of underutilized airspace that is procedurally separated from the conventional airport operations. Therefore, the development of airspace cutouts represents a promising approach to relieve the ATC constraint for VFR UAM operations in some areas.

Fig. 39 New York special flight rules area (SFRA).

Similar to airspace cutouts, a third airspace geometry approach the FAA has previously used to support high volumes of small aircraft operations in controlled airspace is the Low Altitude Authorization and Notification Capability (LAANC) [127].

Fig. 40 displays the LAANC volumes defined within the surface level class B terminal airspace for Boston Logan International Airport. The LAANC volumes are not cut out of the class B airspace like the SFRAs, but rather are areas where the FAA has authorized third party airspace service providers to manage small UAS operations in lieu of FAA controllers. The volumes were determined by controllers to not be used by airport or local aircraft operations. The volumes are made available to small UAS operators through a real-time booking capability hosted by the service providers on the internet.

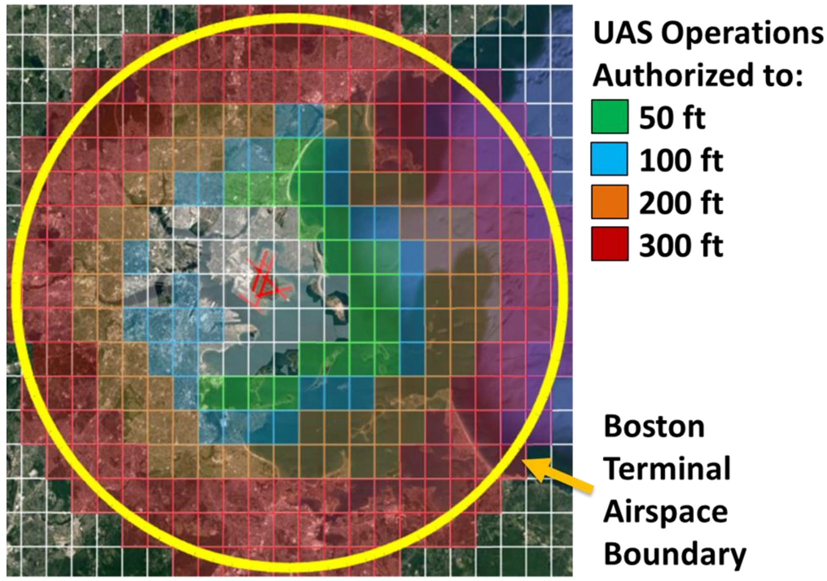


Fig. 40 LAANC volumes for UAS operations at Boston Logan International Airport.
Image © Google, 2019.

Airspace redesign in the Metroplex Project, airspace cutouts, and the LAANC program are all examples of adjustments to airspace geometry to support new operators or higher density VFR flights through the allocation of procedurally segregated airspace.

6.5.3 Traffic Flow Organization

At a high level, airspace may either have a strict flow structure where aircraft are assigned to specific routes, or airspace may be relatively unstructured where pilots, controllers, or automation dynamically select headings and vectors based upon the current traffic situation. Each structure results in different airspace capacities.

Separate analysis by TU Delft [128,129], NASA [130], and U.C. Berkeley [131] indicate that network performance in an airspace is maximized when aircraft operate in altitude layers with prescribed heading restrictions; this structure is similar to existing VFR and IFR cruising altitudes. The freedom of aircraft to select an altitude within the airspace and fly a direct path minimizes flight distance and increases airspace capacity, controller workload notwithstanding. However, these studies assume that aircraft can access any airspace within the study region. The presence of obstacles or inaccessible airspace (such as SUA or airport flight paths) may result in congestion points that degrade the performance of unstructured airspace as noted by TU Delft [128].

To address this limitation, NASA considered optimal traffic structure in the presence of obstacles within urban canyons [132]. Efforts by the University of Washington [133] and Nanyang Technological University [134] also evaluated traffic structure at rooftop height. The results of these three studies indicate that in dense urban scenarios with multiple flight obstructions a structured network (such as the existing VFR helicopter routes) maximizes airspace capacity and also reduces controller workload compared to less organized flights.

The NASA UTM [125] and European U-space [135] projects are each developing approaches to autonomously provide traffic flow management for high-density small UAS (sUAS) operations. They propose to utilize unstructured airspace except in congested flight areas or in proximity to manned operations. Furthermore, they propose a hybrid ATC service model with strategic traffic flow management conducted by an automated, centralized provider, and tactical detect and avoid handled by the aircraft. Simultaneous UTM development programs by Amazon, Google, Uber, General Electric, and numerous other private entities are pursuing similar flight management techniques [136].

6.6 Conclusion

This chapter provided an overview of the potential influence of ATC on UAM operations. Airspace capacity was proposed as the means through which ATC will constrain the scaling of UAM services in metropolitan areas. Three components of ATC were determined to drive airspace capacity, namely:

1. <u>separation minima</u> which sets how closely UAM aircraft may operate to conventional aircraft, to other UAM aircraft, and/or to surface obstacles,
2. <u>controller workload</u> which influences the number of UAM operations that may be supported in airspace where ATC services are provided, and
3. <u>airspace structure</u> which determines where ATC services are provided and how traffic flow is organized.

Separation requirements most severely reduce airspace capacity when controllers apply radar separation and when small aircraft such as UAM are interspersed with large aircraft and subject to wake vortex separation requirements. Furthermore, controller workload creates an upper limit on airspace capacity only in areas where ATC services are provided. Therefore, Chapter 7 evaluates if reducing the size of terminal airspace through the development of airspace “cutouts” (akin to an SFRA) is an effective means to relieve the separation and controller workload limits for UAM scaling.

Airspace cutouts are a potentially promising approach to relieve the ATC constraint. First, existing SFRAs provide a proof of concept for how cutouts may support high density small aircraft operations. Second, the application of pilot (or autonomy) provided visual separation within the cutout relieves scaling limitations due to separation minima. Third, air traffic controllers do not provide ATC services to flights within a cutout; therefore, controller workload does not constrain the scale of operations within a cutout. Finally, similar to the LAANC program for small UAS, airspace cutouts represent areas where new CNS technologies or ATC systems such as NASA’s UTM project may be implemented and matured.

Airspace cutouts therefore represent a promising, low barrier to entry opportunity to increase the feasible scale of VFR UAM operations in the near term, and a pathway to develop technologies and systems to support high-volume IFR operations in the longer term.

The key limitation of airspace cutouts, however, is that they must be procedurally separated from conventional aircraft operations in order to relieve controllers of their responsibility to ensure separation. Cutouts therefore cannot enable UAM operations in close proximity to conventional airports. Considering this, Chapter 8 investigates if advanced flight procedures that leverage reduced separation minima could support high-volume UAM operations to TOLAs located close to conventional airports where procedural separation is not possible.

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7 Potential Allocation of Airspace Cutouts for UAM

The allocation of airspace to develop segregated cutouts within terminal areas was introduced in Chapter 6 as a promising approach to mitigate the influence of controller workload and separation minima for VFR UAM operations. Moreover, airspace cutouts currently support high-volume, small aircraft operations in the U.S. and do not rely on the development of new technologies. This chapter investigates the potential development and benefit of cutouts near large commercial airports.

Fig. 41 notionally displays the concept of airspace cutouts from a terminal area controlled airspace. All UAM flights that enter the terminal airspace boundary are managed by controllers and may be scale-constrained by their workload limitations. However, only UAM flights that pass within the red region of Fig. 41 would potentially experience a loss of separation to conventional aircraft and require active separation management by controllers. UAM operations that occur within the blue regions are "procedurally separated" from conventional flight operations in that the required separation minima are never violated. The blue regions therefore represent areas where one or more airspace cutouts could potentially be developed to support UAM operations.

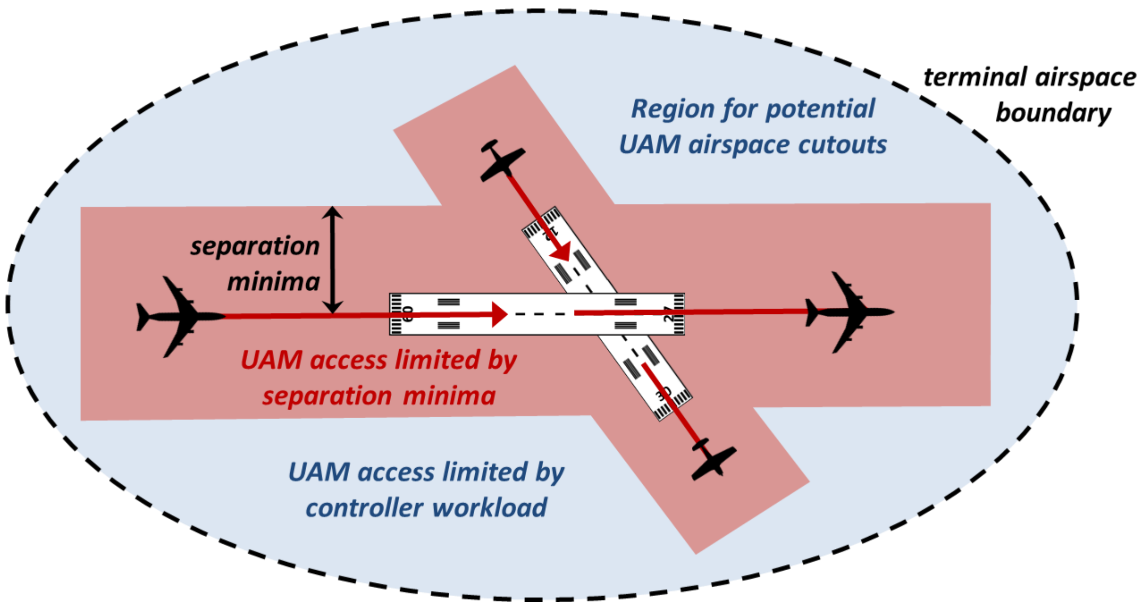


Fig. 41 Notional opportunity for airspace cutouts (blue region) from terminal airspace.

This chapter introduces an approach to analytically identify procedurally segregated airspace where cutouts could be developed for UAM operations. The approach is applied to case studies of terminal airspace in proximity to the Boston, San Francisco, and Atlanta international airports. Comparison between the airports displays differences in the benefits of airspace cutout development for UAM based on airport runway configuration, terminal airspace design, and the dispersion of conventional flight operations.

7.1 Approach

In order to identify procedurally segregated airspace for UAM cutouts, the location of current conventional aircraft operations must be modeled. The approach taken in this thesis was to use radar trajectory data from the FAA Airport Surface Detection Equipment Model X (ASDE-X) to statistically characterize where conventional aircraft operate within terminal airspace. The extent of airspace used by different conventional operators (e.g., large jet aircraft, business jets, helicopters, etc.) was represented as a “containment boundary” that encompassed the volume within which a specified percentile of all flights remained.

Airspace that could potentially be re-allocated to one or more airspace cutouts was then identified by applying separation requirements to the 99.5th percentile containment boundary for large jet aircraft and regional aircraft trajectories (business jets, GA aircraft, and helicopters were assumed to not constrain the development of airspace cutouts due to their greater operational flexibility). Cutouts were developed for three different separation minima (IFR radar, VFR radar, and wake vortex separation requirements) to represent different degrees of procedural segregation for UAM operations. The benefits of each of the three types of cutouts were evaluated through case studies at Boston, San Francisco, and Atlanta international airports.

7.2 Identification of Highly Used Airspace in Metropolitan Areas

To determine airspace utilization by conventional aircraft, current flight operations as recorded by ASDE-X were evaluated in Boston, San Francisco, Atlanta, Newark, and Los Angeles. The radar data provided information on flights that occurred within approximately ten nautical miles of the airports. Of the initial data set, approximately 180 days had a full 24 hours of flight tracking records and were utilized for the analysis; days with incomplete radar data were not considered. The flight tracks were smoothed where necessary and infeasible trajectories (i.e., poor data quality tracks) were discarded.

The flight tracks were sorted into the six operational categories listed below based upon the reported aircraft type and callsign (i.e., flight number). Because GA and helicopter operators did not often report either of these data, the flight tracks for these operators were identified based upon altitude and speed characteristics.

1. large transport aircraft class: >100 passengers (e.g., B737, E170)
2. regional aircraft class: 20-100 passengers e.g., E145, CRJ7)
3. business aircraft class: (e.g., GLF6, LJ70)
4. large GA aircraft class: 6-19 passengers (e.g., C402, BE80)
5. small GA aircraft class: <5 passengers (e.g., SR22, C172)
6. helicopter class

As a first-pass visualization of conventional air traffic location and density, each metropolitan area was discretized into evenly spaced cells where flight densities were displayed as a heat map. Review of the heat maps visually indicated high-traffic airspace where UAM aircraft may not be able to operate and low-traffic airspace where cutouts may be appropriate.

As an example, Fig. 42 displays airspace usage by large transport and regional jet aircraft in proximity to New York City and Newark airport. Fig. 43 then displays how helicopters and small GA aircraft operate in the same airspace using the Hudson River SFRA as a procedurally segregated airspace cutout. Appendix C contains additional heat maps for each of the other airports evaluated.

In Fig. 42 large transport aircraft and regional aircraft exclusively fly on departure or arrival routes to Newark airport when below 2500 ft AGL (an assumed upper cruising altitude for UAM operations within metropolitan areas). Large volumes of airspace surrounding Newark airport experience no or infrequent commercial operations; these areas may support UAM aircraft flights with no interaction or loss of separation to conventional flights. The Hudson River SFRA, a current airspace cutout for GA operations, is highlighted in green in Fig. 42 as an example of such an area.

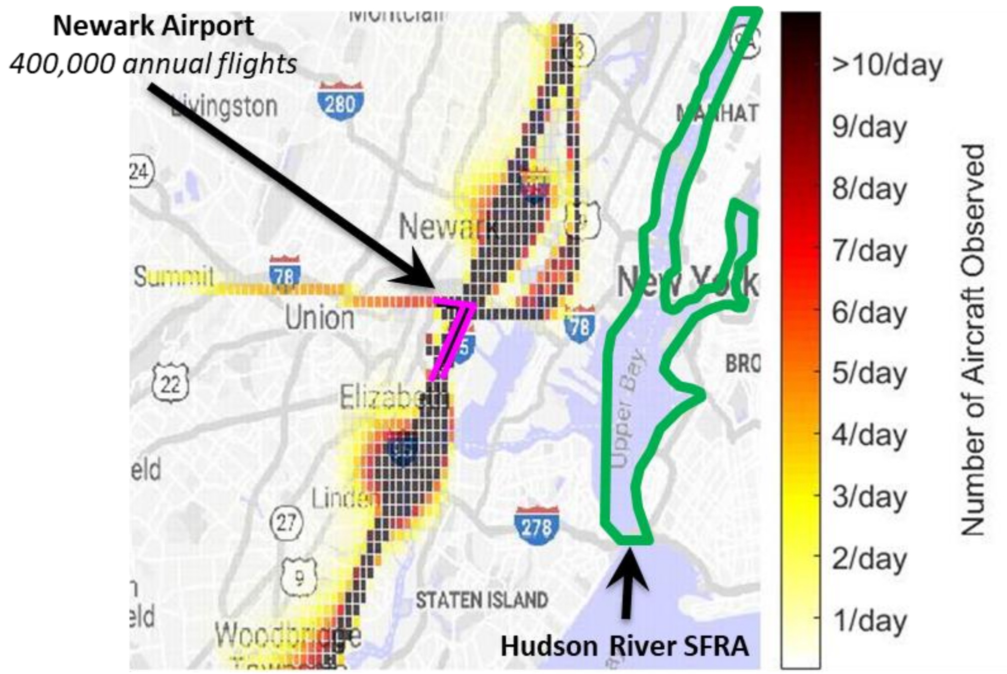


Fig. 42 Frequency of large transport and regional aircraft operations below 2500 ft AGL in New York and New Jersey.

GA and helicopter operations are more distributed over New York and utilize many smaller airports and helipads as shown in Fig. 43. The Hudson River SFRA supports the densest helicopter and GA operations in the region. Approximately 50 flights per day were identified from the radar tracks; however, as many as a few hundred helicopter and GA operations per day were anticipated to occur in the SFRA based on reported traffic numbers [63]. The SFRA acts as a conduit for traffic passing through New York City and it also is a feeder route for aircraft to and from heliports (such as Kearny) and GA airports (such as Linden) located within the controlled airspace next to the SFRA.

The number of GA and helicopter tracks presented in Fig. 43 is less than the number of operations reported by the airports. This indicated the speed and altitude-based algorithm used to identify GA and helicopter tracks (in lieu of aircraft type which was not frequently reported) may have failed to capture all of these operations. It was also possible the ASDE-X radar did not capture all GA operations that occurred outside the equipped airports, especially those flights at the limit of its coverage range.

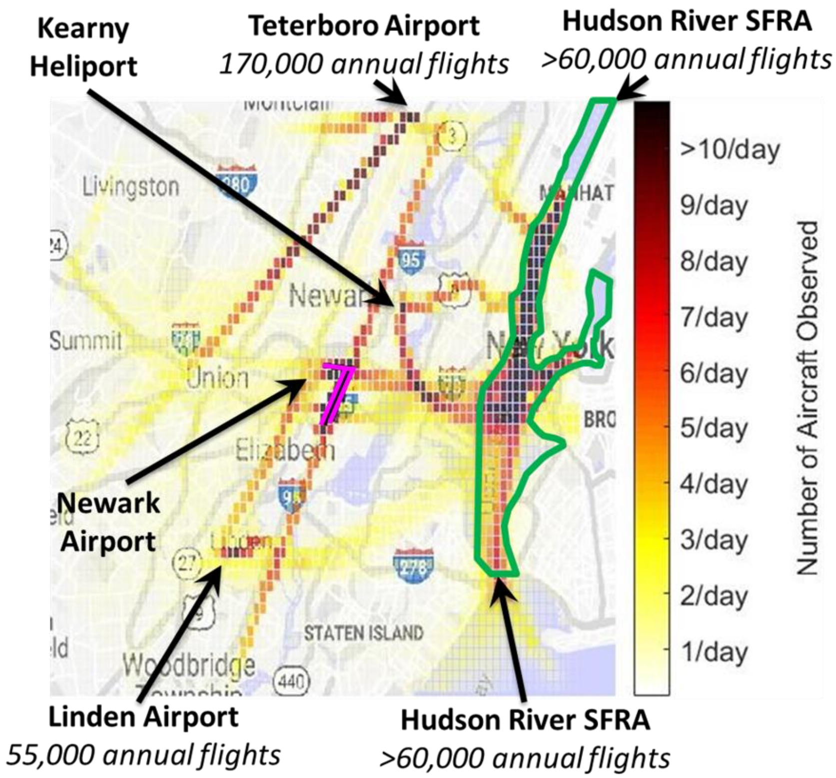


Fig. 43 Frequency of GA and helicopter operations below 2500 ft AGL in New York.

Fig. 44 presents a heat map of GA and helicopter operations in the Los Angeles area. A number of helicopter and VFR routes created concentrated areas of flights in the region, especially above highways. Santa Monica Airport also exhibited a large dispersion of flights on multiple approach patterns and its downwind segment. Finally, five separate routes, including an SFRA, passed through the Los Angeles International Airport (LAX) airspace near the runways. Fig. 45 presents greater detail on these crossing routes.

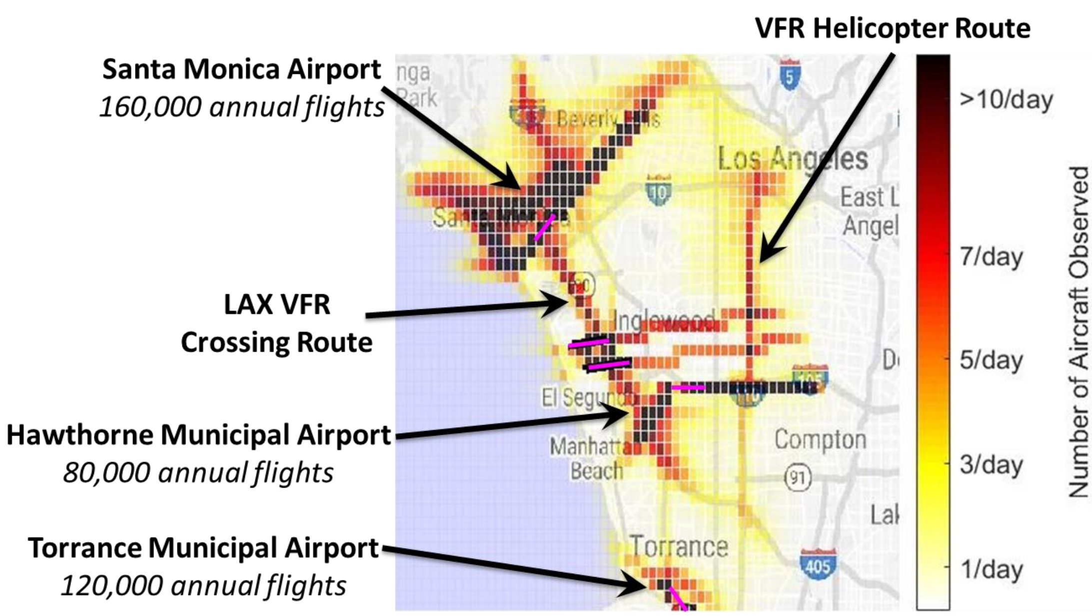


Fig. 44 Frequency of GA and helicopter operations below 2500 ft AGL in Los Angeles.

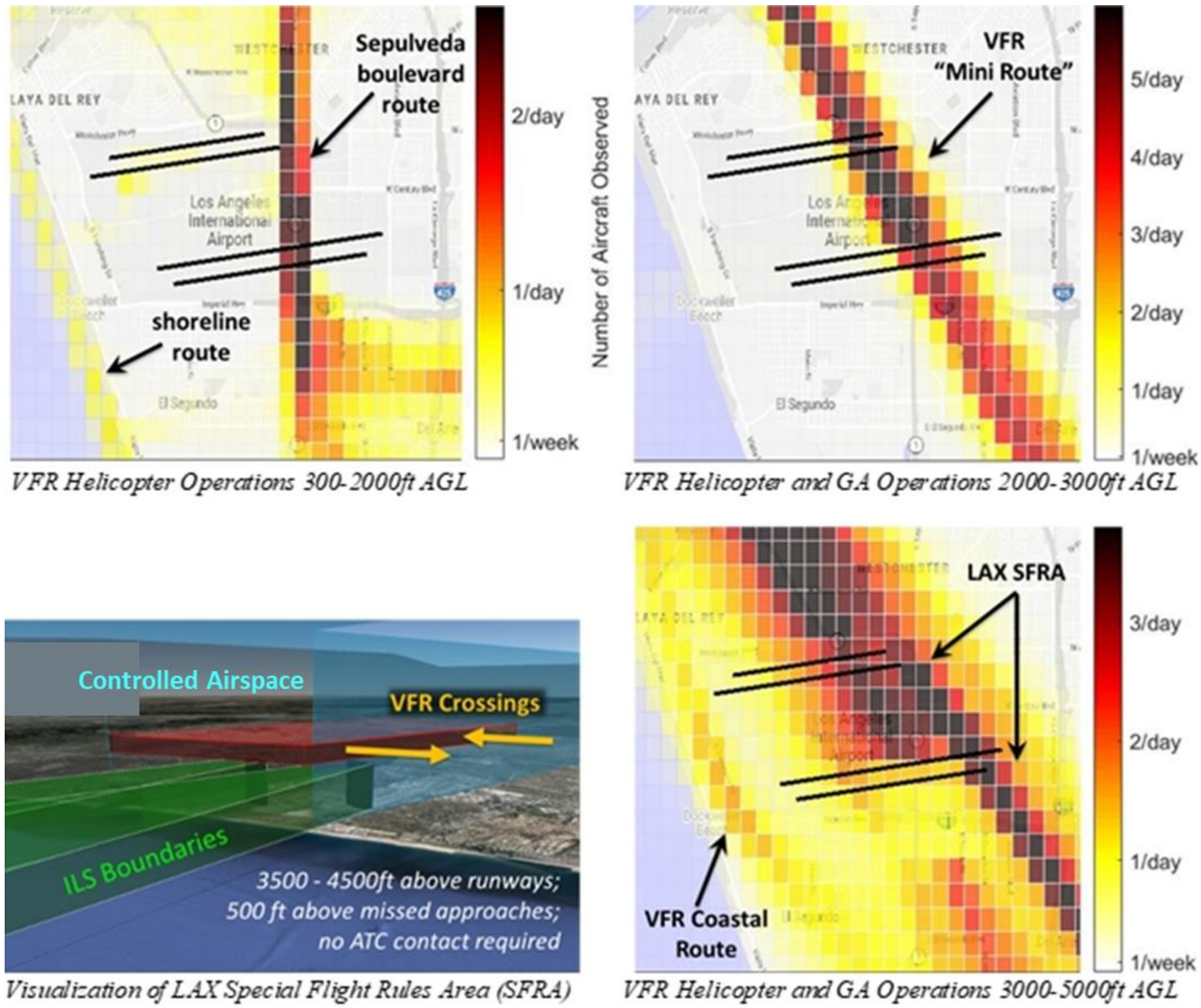


Fig. 45 Helicopter and GA crossing routes at LAX.

In Fig. 45, the Sepulveda boulevard route was especially interesting due to the high degree of navigational accuracy with which the helicopters operate. The pilots were authorized by ATC to enter the airspace and then visually follow the boulevard to cross the airport. These helicopters (and perhaps future UAM aircraft) were capable of *VFR* operations in safety critical areas with similar levels of navigational accuracy to instrument flight. Fig. 115 in Appendix C displays GA operations near San Francisco International Airport (SFO) that operated under VFR with similar levels of navigational accuracy by not crossing Highway 101 towards the airport.

Furthermore, the SFRA over LAX is an example of a separate means through which airspace cutouts previously supported high-volume GA operations. Unlike the SFRA in New York which is *laterally* separated from commercial operations in the vicinity and extends from the surface up to 1300 ft mean sea level (MSL), the LAX SFRA is *vertically* separated from conventional flights below it. The analysis in this chapter does not evaluate the potential for vertically separated airspace cutouts *above* conventional traffic such as the LAX SFRA. Procedural separation above an airport depends upon the missed approach altitudes for procedures and the willingness of controllers to ensure that separation is provided during go-around or missed approach operations.

Considering that high densities of large transport aircraft or regional jet trajectories only existed on airport approach and departure paths, the remainder of the analysis evaluated airspace cutouts that provide separation from arriving or departing flights. It was assumed that UAM flights would not be segregated from helicopter and GA operations.

7.3 Modeling Airspace Used by Conventional Flights

In order to identify airspace that is procedurally segregated from conventional flights, "containment boundaries" were generated around arriving and departing large transport and regional aircraft trajectories. The containment boundaries statistically describe the airspace that was flown in by a specified percentile of the aircraft operations. By varying the inclusion of the containment boundaries from the 95th percentile flight up to the 100th percentile flight, different probabilities of interaction between UAM and conventional aircraft were assessed.

To develop the containment boundaries, departing and arriving flights were distinguished by identifying if their initial or final radar report was located on the surface of the airport, respectively. Aircraft that executed a missed approach were distinguished from completed arrivals as flight tracks that either descended at least 1000 ft below their initial altitude or below 3000 ft AGL, and then rose at least 400 ft above their minimum altitude. Potential missed approach paths were manually checked for validity and assigned to the approach runway. Arriving and departing operations were assigned to the runway they touched down or lifted off from, respectively.

Fig. 46 presents a containment boundary for arrivals to runway 19R at SFO. The containment boundary consists of a discrete number of "sample boxes" that are normal to the mean trajectory. The height and width of each sample box were defined to include a specified percentile of the flight tracks at the along-track distance of the box. Along-track distance was measured for all trajectories from the demarcation bar or threshold at the far end of the runway for arrivals, and from the starting end of the runway for departures. This reference point on the runway accomodates different starting or ending points of the radar tracking data and calculates trajectory dispersion at equal distances from the airport.

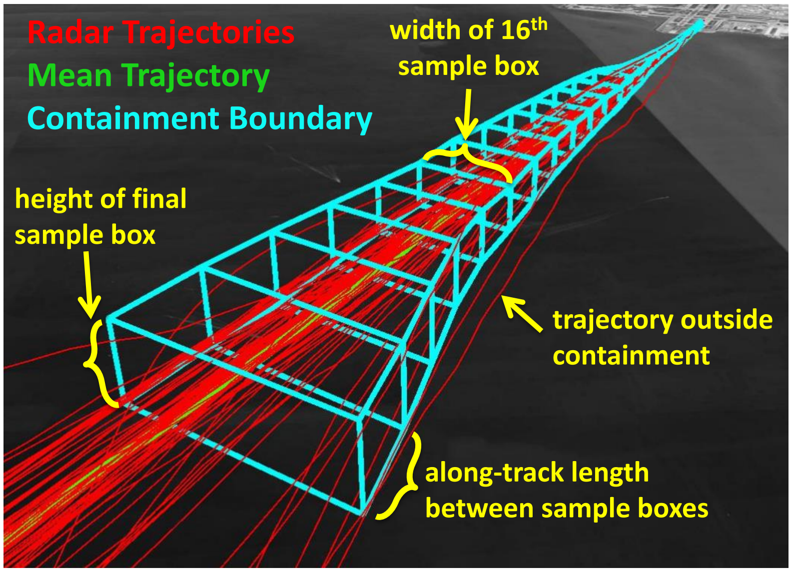


Fig. 46 Example trajectory containment boundary for arrival flights.

Fig. 47 displays an example of a single sample box viewed normal to the mean flight trajectory. If the containment boundary was specified to capture the 95th percentile flight, then the lower altitude corresponds to the 2.5th percentile trajectory and the upper altitude corresponds to the 97.5th percentile trajectory. Excluding points that were beyond the specified percentile in both the vertical and lateral direction results in the containment boundary inscribing fewer total points than the specified percentile. However, this was deemed to be appropriate as air traffic is managed by providing either vertical or lateral separation, so the two dimensions may be considered separately.

Greater detail on the methodology used to calculate the containment boundaries may be found in Ref. [137].

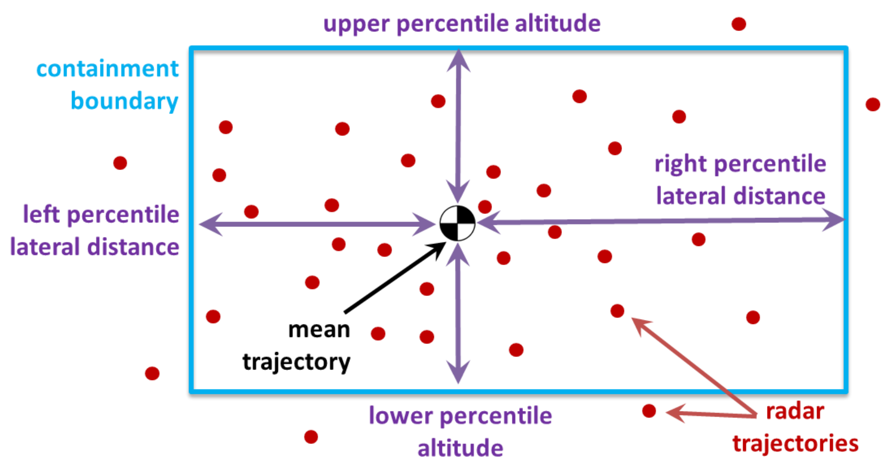


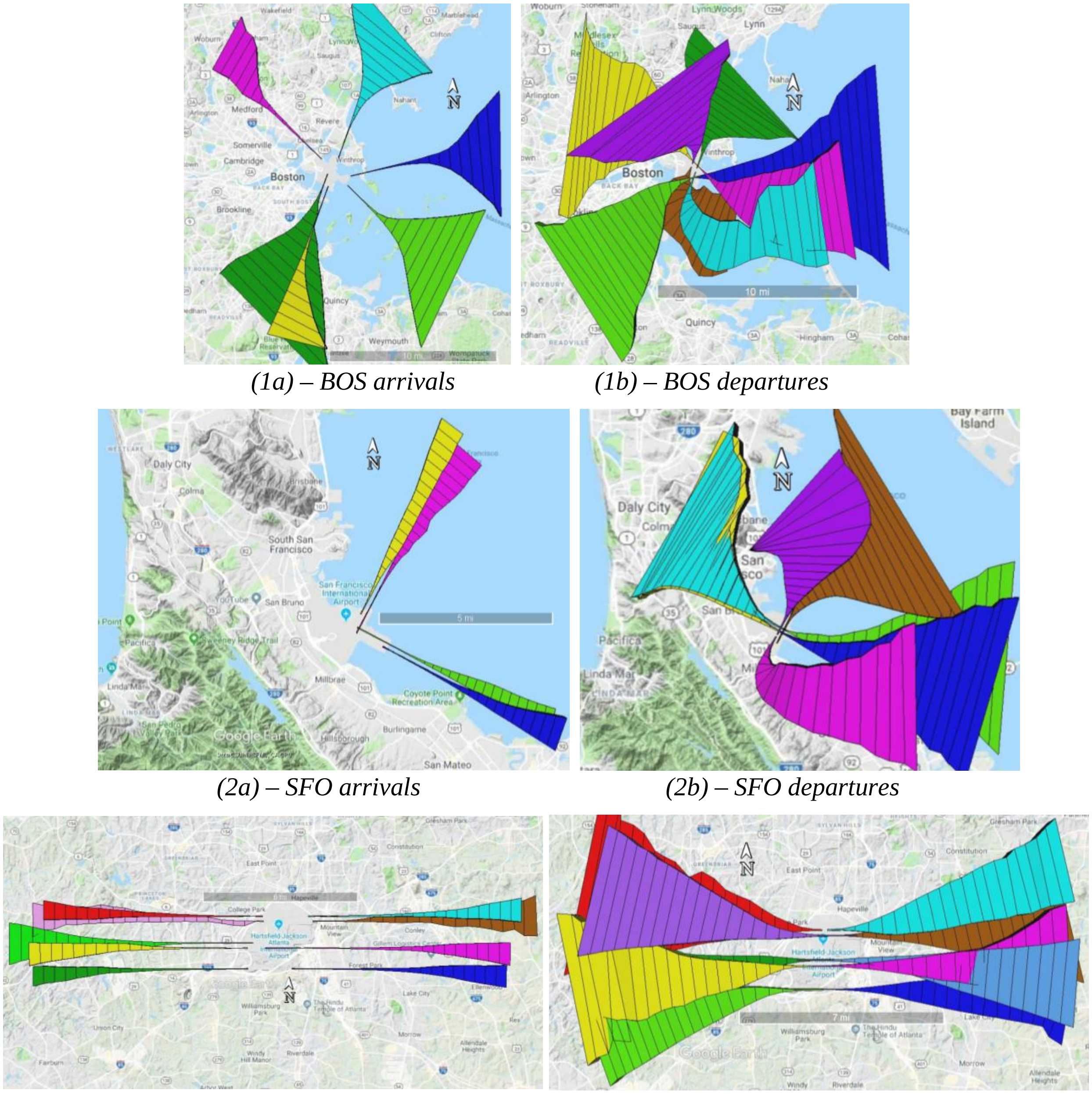
Fig. 47 Example trajectory containment sample box displaying calculation approach at one along-track location.

7.3.1 Generation of Containment Boundaries

Containment boundaries were generated for transport and regional aircraft arrivals and departures at San Francisco (SFO), Atlanta (ATL), and Boston (BOS) international airports. The boundaries were created for 95th, 99th, 99.5th, 99.9th, and 100th percentile containment. Fig. 48 displays the 99.5th percentile containment boundaries at the three airports.

Variation in the size and shape of the containment boundaries is the result of differences in the airport layout, flight procedures, and surrounding terrain. These differences may impact the potential benefit and design of airspace cutouts for UAM operations.

For example, departure operations in Fig. 48 displayed greater dispersion of flight trajectories and resulted in larger containment volumes than arrivals. In sub-figure (1a), a fanning effect for arrivals to Boston was present from more aggressive aircraft vectoring onto final approach. Aircraft approaches such as those to runway 04R (yellow) and 15R (magenta) in sub-figure (1a) were nearly exclusively vectored onto the procedure from only one direction resulting in an asymmetric fanning affect. In comparison, the other runways at BOS accepted aircraft from both directions creating a more symmetric fanning affect.



(1a) – BOS arrivals *(1b) – BOS departures*

(2a) – SFO arrivals *(2b) – SFO departures*

(3a) – ATL arrivals *(3b) – ATL departures*

Fig. 48 99.5th percentile containment boundaries for 180 days of ASDE-X radar data sorted by runway at Boston (BOS), San Francisco (SFO), and Atlanta (ATL) airports.

Arrivals to SFO in sub-figure (2a) did not display a pronounced fanning affect; however, the trajectory data at SFO only extended to approximately four NM from the threshold while a majority of fanning in BOS occurred at further along-track distances. Arrivals to ATL in sub-figure (3a), on the other hand, have less fanning and smaller containment boundaries than either SFO or BOS, likely as a result of simultaneous operations to multiple, parallel runways. The difference in dispersion impact the size of the containment boundaries and how closely to the airport airspace cutouts may be defined.

7.3.2 Containment Boundary Variation with Percentile Inclusion

Fig. 49 presents the effect of different percentiles of trajectory inclusion on the containment boundary size for arrivals to BOS runway 27. From the figure, a significant expansion in containment width is visible in the 99.9th (magenta) and 100th (cyan) percentile cases compared to the lower trajectory inclusion levels. The 99.5th percentile and lower containment boundaries have similar widths, especially within four NM of the runway threshold. This trend is consistent across arrivals and departures at all three airports as discussed further in Ref. [137].

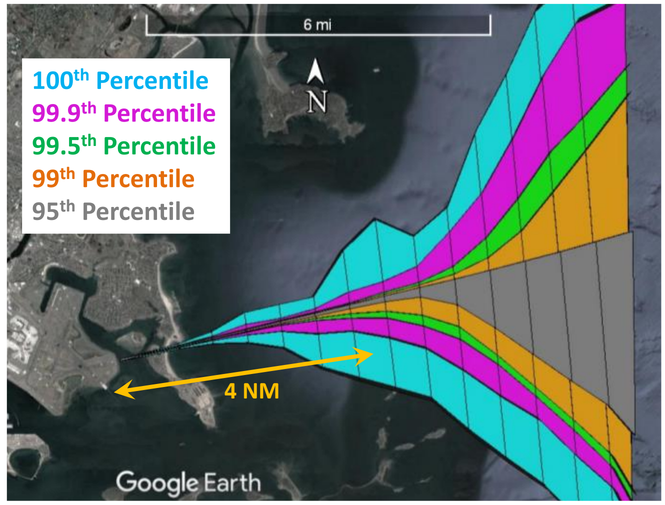


Fig. 49 Containment boundary variation with percentile for 9,000 large transport aircraft arrivals to BOS runway 27.

Considering that less than 1 in 200 flights use the additional airspace within the 99.9th or 100th percentile containment boundary, it was assumed that these flights were non-standard approach operations. If these non-standard trajectories were due to more aggressive ATC vectoring during night-time or low-traffic periods, for example, they may be flown similar to the vast majority of flights if cutouts were developed.

The 99.5th percentile containment was therefore used for the identification of airspace cutout opportunities. Future work could enhance the validity of this assumption by isolating the cause of flight deviations for the non-standard flight and assessing their ability to be flown more on the standard procedure.

7.3.3 Missed Approach Operations

The trajectory containment boundaries in Fig. 48 *did not* include missed approaches. Missed approach operations may utilize airspace that is otherwise procedurally segregated from typical arrivals and departures.

Fig. 50 displays 70 missed approach operations identified for Atlanta's west flow configuration; the 99.5th percentile approach and departure containment boundaries are plotted for perspective. Although the missed approach operations in Fig. 50 laterally access airspace not used by ordinary arrivals and departures, further evaluation of the trajectory data revealed that all but one of the 70 flights turned off the runway centerline only after achieving an altitude of 1000 ft AGL or greater (the outlier flight turned off at 750 ft). Each trajectory gained altitude rapidly to at

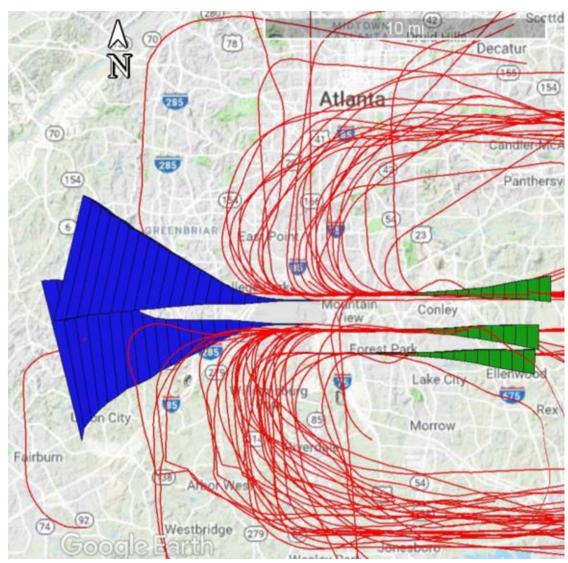


Fig. 50 Missed approach trajectories (red) for ATL in west flow configuration. *99.5th percentile arrival (green) and departure (blue) containments.*

least 3500 ft MSL (as specified in the missed approach procedures) before returning to the arrival procedure. In this example at ATL, an airspace cutout for UAM north or south of the airport may need to consider the providing of vertical separation to missed approaches.

Analyses of airport operations found missed approaches to occur at a rate of approximately one per every thousand flights [138,139]. With this low frequency of occurrence, controllers may have flexibility to manage interactions between UAM cutouts and aircraft on missed approach. For example, while controllers will frequently vector aircraft off missed approach procedures early to accelerate re-entry into the arrival queue, in the presence of UAM cutouts this practice may be curtailed. The development of airspace cutouts may also result in design modifications to missed approach procedures to ensure separation.

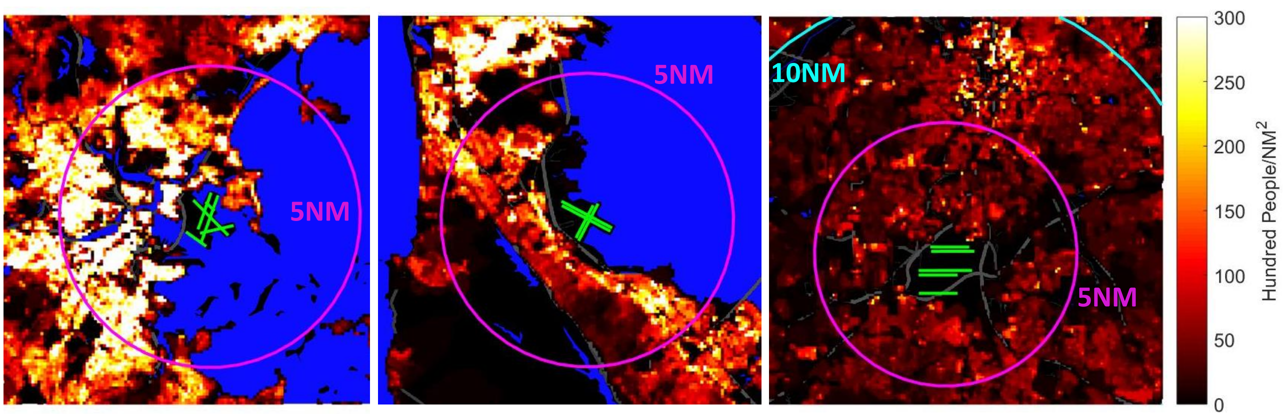
Considering the low frequency of missed approaches and the flexibility with which controller may handle these operations to provide vertical separation to cutouts, the impacts of missed approach operations on the development of airspace cutouts were not considered further in this thesis.

7.4 Case Studies of Airspace Cutout Development for UAM

SFO, ATL, and BOS exhibit different contextual factors anticipated to influence the feasibility of airspace cutouts in the terminal area. These factors include their runway configuration, the proximity of flight obstructions to the airport, the proximity of the airports to populated regions, and the type of approach procedures used by conventional aircraft.

Fig. 51 displays the runway layout and location of each airport with respect to the population of the surrounding areas. BOS is located closest to the city center (west of the airport) and has multiple runways that create overflight of population-dense regions. As a result, the surface-level controlled airspace at BOS currently restricts UAM access to a majority of the city. Airspace cutouts could substantially increase UAM access to areas of demand if they may be developed near BOS.

SFO is located south of the city center with operations conducted primarily over water where airspace cutouts may provide less value to UAM operations. ATL is located furthest from the city center and flights land or depart exclusively to the east or west of the airport.



Boston *San Francisco* *Atlanta*

Fig. 51. Runway layout (green) and proximity to populated regions for each airport.

7.4.1 Static and Dynamic Cutout Development

Two concepts for airspace allocation to UAM cutouts were considered in the case studies: *static* cutouts and *dynamic* cutouts.

A static cutout, such as the New York or LAX SFRAs, is always active and provides procedural separation to airport operations independent of the traffic flow pattern and procedures in use at the airport. Static cutouts are advantageous in that a UAM aircraft consistently have access to the cutouts, weather permitting. Static cutouts are also less complicated to implement than dynamic cutouts as introduced below.

A dynamic cutout only provides procedural separation to airport operations for a specific traffic flow pattern. When airports shift traffic flow pattern air traffic controllers activate a pre-defined set of dynamic cutouts for the new flow pattern and close the set of cutouts suitable for the prior flow pattern.

The benefit of dynamic cutouts is they may enable UAM to access additional airspace and surface areas that are not procedurally separated from all arrival or departure procedures, especially those that are infrequently used. However, dynamic airspace allocation adds complexity as the availability of each cutout must be effectively communicated to all aircraft, and controllers must have the ability to ensure that the cutouts may be vacated in a specified amount of time when an airport changes its flow pattern [42].

Dynamic airspace allocation has a number of precedents in the current ATC system. First, most SUA are a form of dynamic airspace. These volumes are activated and deactivated around the schedules of sporting events, VIP movements, military exercises, or other activities. Pilots are alerted to the status of a SUA either through publication in the VFR sectional chart, or through a NOTAM generally released with a few days lead-time. Second, TRACON's routinely change their sector definitions in order to maximize airspace capacity and reduce controller workload when major airports shift flow pattern[140]. Third, dynamic airspace management was proposed as an element of the Next Generation Air Transportation System as a means to adjust sector boundaries in real-time in response to weather or heavy traffic [141].

Both static and dynamic fine-scale airspace allocation were considered in the case studies.

7.4.2 Case Study Approach

The approach of the case study was to:

1. Model the airspace currently used by conventional arrival and departure operations. 99.5th percentile containment boundaries for transport and regional aircraft were developed for arrivals and departures at each airport as discussed in Section 7.3.
2. Identify surface obstacles that penetrate into airspace. Obstacle data were collected from the FAA Digital Obstacle File (DOF)[12] and are presented as feet above airport elevation in the analysis. While the DOF only contains obstacles in the immediate vicinity of airports,

[12] www.faa.gov/air_traffic/flight_info/aeronav/digital_products/dof/

the scope of the data was sufficient for the airspace cutout analysis as the cutouts were also located in close proximity of the airports.

3. Determine the airspace that was procedurally segregated from each containment boundary by one of three types of separation minima and could support UAM flights at a specified minimum cruising altitude. The three separation minima considered were the IFR radar requirements, VFR radar requirements, and wake vortex requirements. Three different sets of airspace cutouts were therefore identified for each containment boundary (i.e., one set of cutouts for each type of separation minima).
4. Generate the static cutout opportunity by finding the intersection region for the cutouts of every containment boundary. To generate the dynamic cutout opportunities, the intersection region for the cutouts of the containment boundaries associated with an active arrival or departure were determined for each airport flow configuration.

Separation requirements from surface obstacles may limit the utility of airspace cutouts in some areas. Fixed-wing aircraft must remain 1000 ft above or 2000 ft laterally from obstacles in congested areas during cruise, or 500 ft away from obstacles elsewhere. Helicopters must maintain a safe emergency landing altitude and not cause hazard to persons or property. Interviews conducted by the author with helicopter pilots suggested they routinely fly within 200 to 500 ft of obstacles.

Three types of procedural separation were modeled in the case studies:

1. <u>IFR Radar Separation</u>: airspace that is a minimum of 3.0 NM laterally or 1000 ft vertically from the containment boundaries fulfills the IFR radar separation minima. Part 135 UAM helicopters have a minimum regulatory cruise altitude for passenger carrying operations of 300 ft AGL in congested areas; for fixed-wing aircraft this minimum is 500 ft during the day and 1000 ft at night. Furthermore, both types of aircraft are required to remain 1000 ft above obstacles or the surface when operating under IFR.

   In the case studies an IFR cutout was developed based on the helicopter minimum cruise altitude with no surface obstacles. The IFR cutout therefore began when the containment boundary floor was greater than 1300 ft AGL (i.e., allowing 1000 ft of separation to a UAM flight at 300 ft). Although aircraft cannot currently operate under IFR in an airspace cutout, this scenario was evaluated as future CNS and automation capabilities could enable such capabilities.
2. <u>VFR Separation</u>: airspace that is a minimum of 1.5 NM laterally or 500 ft vertically from the containment boundaries meets the VFR radar separation minima. With a 300 ft UAM cruising altitude floor, a VFR cutout was modeled when a containment boundary floor was greater than 800 ft AGL.
3. <u>Lateral Wake Vortex Separation</u>: although current flights are not authorized within the VFR radar separation minima without providing visual separation to conventional operations, a future scenario is modeled where the requirement for visual separation is relaxed and the cutout is defined for the wake vortex lateral separation minima of 2500 ft. The vertical separation requirement was assumed to remain 500 ft requiring a containment boundary floor of greater than 800 ft AGL.

The modeling assumptions and scenarios in the case studies were intended to provide a first-pass estimate of the potential benefit of airspace cutouts to relieve the ATC scaling constraint for UAM. Future research should consider the sensitivity of cutouts to different UAM aircraft minimum flight altitudes, obstacle separation requirements, and UAM flight below 300 ft AGL during approach or departure procedures.

7.4.3 Airspace Cutout Potential Near Atlanta International Airport

Fig. 52 displays the regions surrounding ATL where *static* airspace cutouts could potentially be developed to meet the IFR, VFR, and wake vortex separation requirements. In Fig. 52, the ATL runways are indicated at the center of the diagram as black bars. Containment boundaries are indicated in purple and extend from the ends of the runways to display the lateral extent of airspace used by 99.5% of transport and regional jet operations. The surface-level controlled airspace surrounding ATL is notated with a black dashed line.

The airspace that could potentially be allocated to an IFR cutout is indicated with a green tint. The airspace that could be potentially allocated to a VFR cutout is tinted blue, and the airspace for the wake vortex cutout is tinted red. The area within the solid red line represents a region within 2500 ft laterally and less than 500 ft vertically of the containment boundaries where none of the cutouts could provide procedural separation.

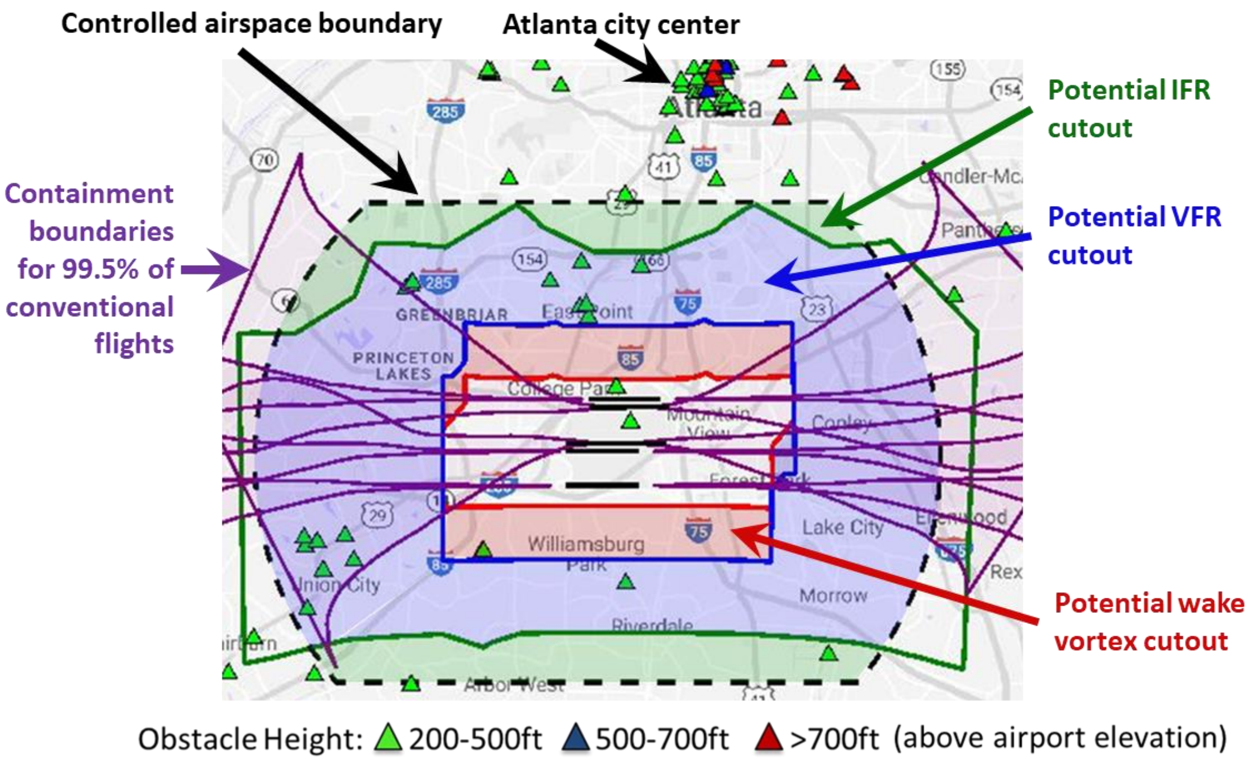


Fig. 52 Static airspace cutout opportunity for UAM at ATL.

Due to the location of ATL eight miles south of the Atlanta city center, UAM flights may operate in the city center beyond the controlled airspace boundary without the need for a cutout. However, airspace allocation to new cutouts can provide substantial access to the communities south of the city center that are currently within ATL's controlled airspace.

As visible in green in Fig. 52 and quantified in Table 19, 16% of the controlled airspace may be re-allocated to a static IFR cutout. More significantly, static VFR cutouts inside the blue region could enable UAM aircraft to access 73% of the ATL surface-level controlled airspace. Access to the red region through a notional wake vortex cutout would support access to an additional 12% of the controlled airspace over the VFR cutouts.

The static cutout volumes presented in Fig. 52 are applicable to either of ATL's two traffic flow patterns. Fig. 53 presents the dynamic cutout opportunities when ATL is in a west traffic flow pattern. ATL operates in a west flow pattern 64% of the year based on reports from the FAA Aviation System Performance Metrics.

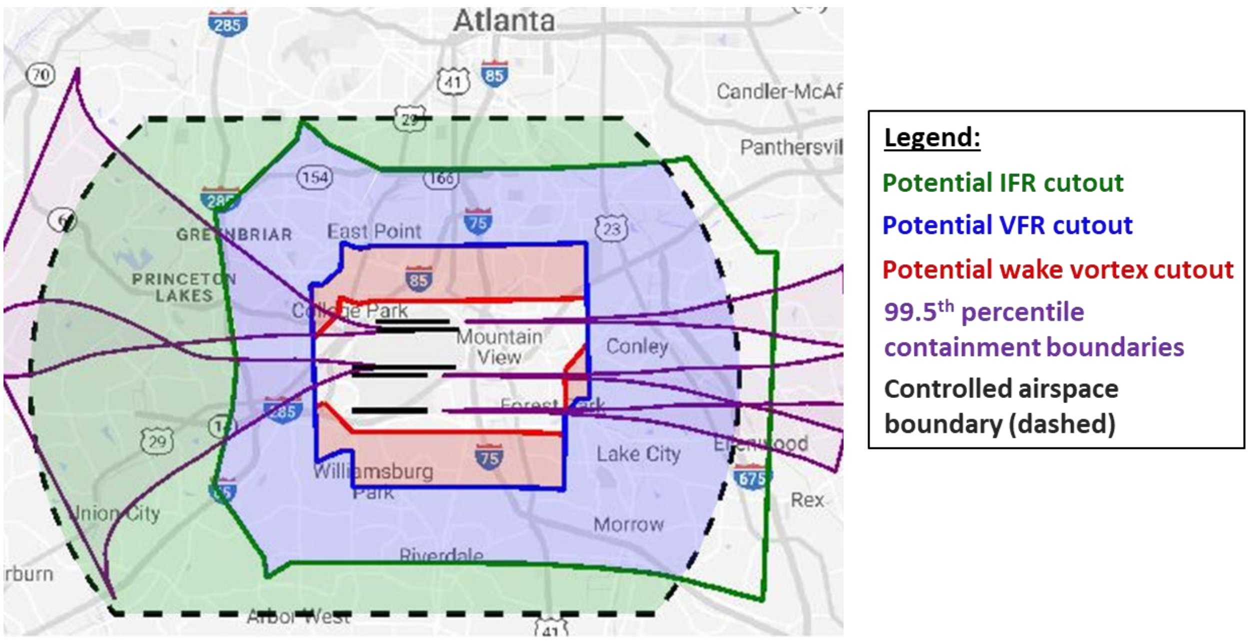


Fig. 53 Dynamic airspace cutout opportunity for UAM at ATL in a west flow pattern (64% frequency).

A dynamic IFR cutout increases potential controlled airspace access to nearly 40% (compared to 16% in the static case) without ATC interaction. The majority of this additional benefit results from under flight of the conventional aircraft departures to the west of the airport. The benefit of dynamic VFR and wake vortex cutouts compared to static cutouts at ATL is less significant and only provides an additional 7% and 4% of access, respectively. The potential benefits from dynamic cutouts in an east flow pattern are of a similar magnitude as displayed in the second row of Table 19, however the actual location of the cutouts is changed to the east side of ATL.

Table 19 displays the percentage of controlled airspace at all three airports that could potentially be released to UAM operations through each of the three cutout scenarios in a dynamic or static implementation.

Table 19. Potential impact of airspace cutouts at three case study airports.

	Airport Flow Pattern	% of Year Active	*% of Controlled Surface Area Available to UAM Through:* IFR Cutout	VFR Cutout	Wake Vortex Cutout	Cutout Type
Atlanta	West	64%	39%	80%	89%	Dynamic
	East	36%	31%	80%	89%	
	All	100%	16%	73%	85%	Static
Boston	Northwest	37%	50%	89%	95%	Dynamic
	Northeast	18%	18%	82%	89%	
	Southwest	28%	57%	87%	95%	
	Southeast	17%	40%	88%	95%	
	All	100%	13%	77%	85%	Static
San Francisco	West (low wind)	83%	51%	85%	94%	Dynamic
	West (high wind)	13%	49%	83%	94%	
	South	3%	55%	85%	94%	
	All	100%	36%	79%	90%	Static

	Static IFR Cutout	Static VFR Cutout	Static Wake Vortex Cutout
Average:	22%	76%	87%

7.4.4 Airspace Cutout Potential Near Boston International Airport

As a result of Logan airport's location two miles east of the Boston city center, its class B airspace covers the majority of the metropolitan core. Furthermore, due to frequently changing wind patterns, BOS operates in four flow patterns that distribute arrivals and departures throughout the controlled airspace. Fig. 54 displays BOS in northwest flow, the most frequent pattern.

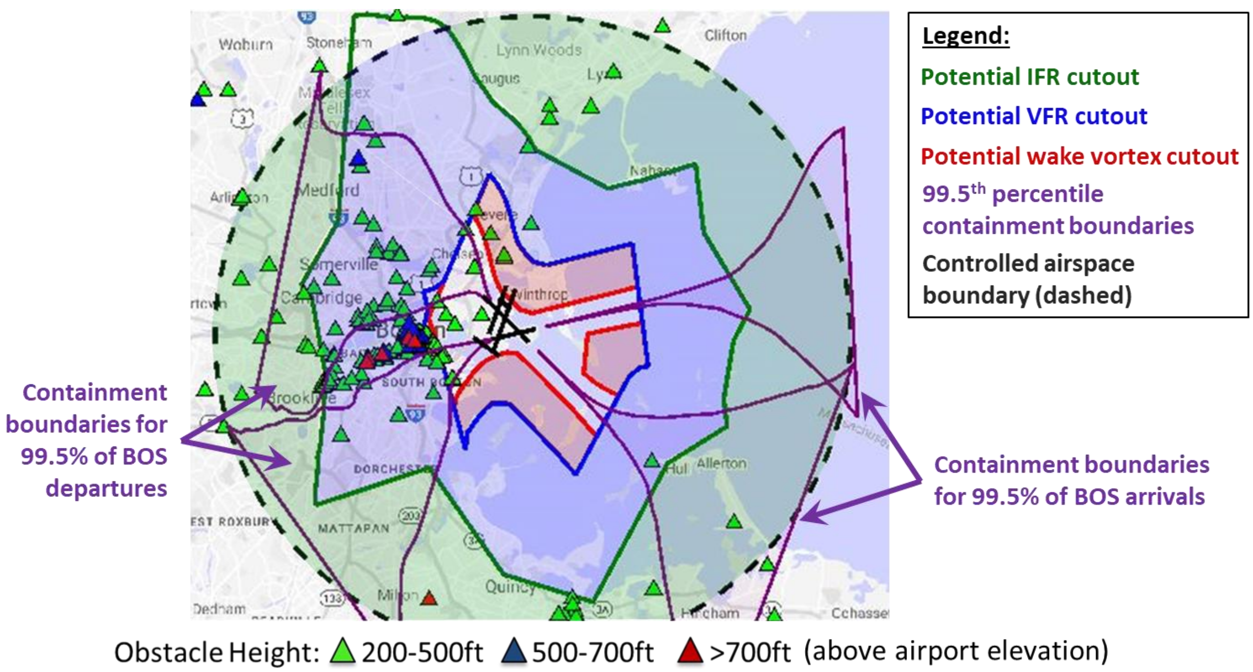
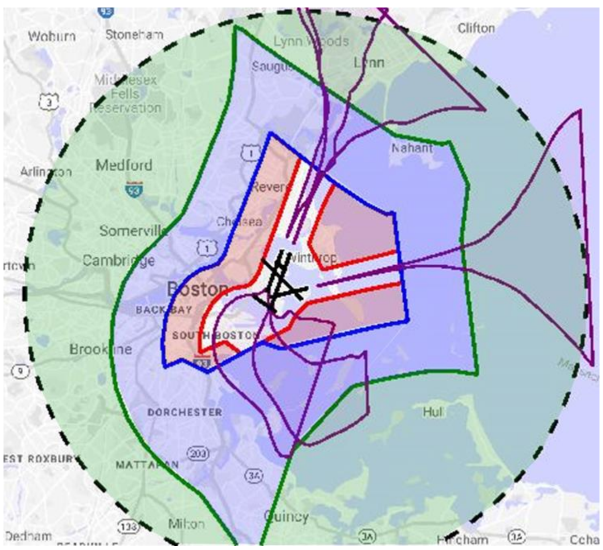


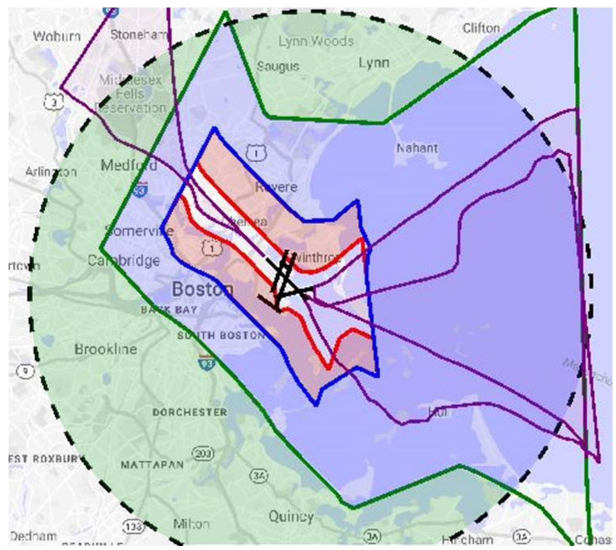
Fig. 54 Dynamic airspace cutout opportunity at BOS in northwest flow (37% frequency).

Despite the larger dispersion of arriving and departing flights at BOS compared to ATL, dynamic IFR and VFR cutouts for the northwest flow pattern may support UAM access to as much as 50% and 89% of the BOS surface-level controlled airspace without ATC interaction, respectively. However, the large number of surface obstacles protruding into the airspace west of the airport in Fig. 54 may challenge the feasibility of UAM flight within the cutouts. Obstacles in the region routinely reach up to 700 ft AGL. Due to obstacle separation criteria, UAM aircraft may not be able to access the city center at a cruising altitude of 300 ft AGL as modeled, especially in IMC.

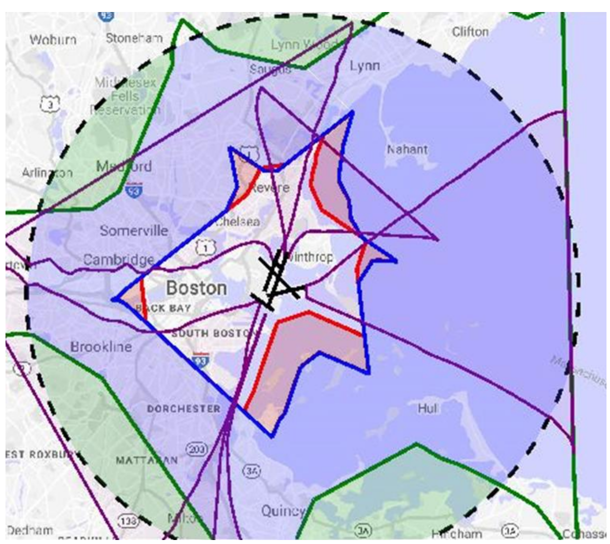
Another complicating aspect for the airspace cutout concept at BOS is the frequency with which the airport changes flow pattern. It is not uncommon for the airport to operate in all four flow patterns over the course of a single day. The crossing runways at BOS result in substantially different cutout locations and benefits between the flow patterns. Fig. 55 displays this change in the three other flow patterns at BOS (the plotting of obstacles has been removed for clarity).



Southwest Flow – 28% annual usage



Southeast Flow – 17% annual usage



Northeast Flow – 18% annual usage

Fig. 55 Airspace cutout opportunities at BOT for three additional traffic flow patterns.

The northeast flow pattern is the most constraining scenario for cutouts at BOS. This is the result of arrivals to runways 04L and 04R which pass at low altitudes over the city center. Arrivals to runway 04L in particular exhibited larger dispersion than arrivals to any other runway of the three airports evaluated. The containment boundaries for departures in the northeast flow pattern, especially from runway 09, gain altitude more slowly than in the other configurations resulting in less opportunity for cutout development. This trend is discussed further in Section 7.4.6.

While dynamic cutouts in the southeast and southwest configurations may enable a similar volume of airspace to be accessed, the location of the cutouts shift significantly.

In southwest flow, aircraft depart towards the city center before turning out over the bay. As a result, a large percentage of the city center is unable to be accessed through a VFR cutout. The benefit of defining a cutout based on the wake vortex limits is greater for this airport flow pattern as access to the pink region enables UAM to access much of the city center. The southeast flow pattern supports the largest opportunity for cutouts in the primary city center, but limits the potential for cutouts northwest of the airport.

Opportunity for IFR static cutouts in Boston is only 13% of the class B airspace compared to dynamic cutout opportunity for as much as 57% of the airspace as shown in Table 19. Static VFR cutouts may provide access to over 75% of the surface-level controlled airspace, however, which is greater than the static VFR cutout potential in Atlanta.

The reduced potential for IFR static cutouts in Boston is largely the influence of the northeast flow pattern and attests to the potential value of a dynamic airspace cutout concept. Furthermore, the frequency of runway flow pattern change at BOS indicates the importance of accurate weather prediction in order to anticipate which dynamic cutouts may be available and what UAM trips could be completed. Research into runway flow pattern prediction by Murca & Hansman [142] are initial efforts towards supporting such a capability.

7.4.5 Airspace Cutout Potential Near San Francisco International Airport

SFO is located 11 miles south of downtown San Francisco and its surface-level controlled airspace does not affect UAM operations in the city center. Cutout opportunities around SFO are displayed in Fig. 56 for the airport's primary flow pattern which is active 83% of the time.

In Fig. 56, a large volume of controlled airspace west of the airport is available for an IFR cutout. This area also remains separated in the other SFO flow configurations. Interestingly, the SFO airspace was redesigned in late 2018 (the redesign was not considered in Fig. 56 or the analysis in this thesis) to re-allocate much of controlled airspace west of the airport as Class E airspace as noted in Fig. 38. This natural experiment demonstrates how airspace that is procedurally segregated from conventional arrival and departure operations may be released for the operation of small aircraft such as UAM.

SFO exhibited the most stable runway flow pattern of the three airports, and also the least difference between the benefits of static or dynamic cutouts. As a result, this area may be especially well-suited for the development of airspace cutouts.

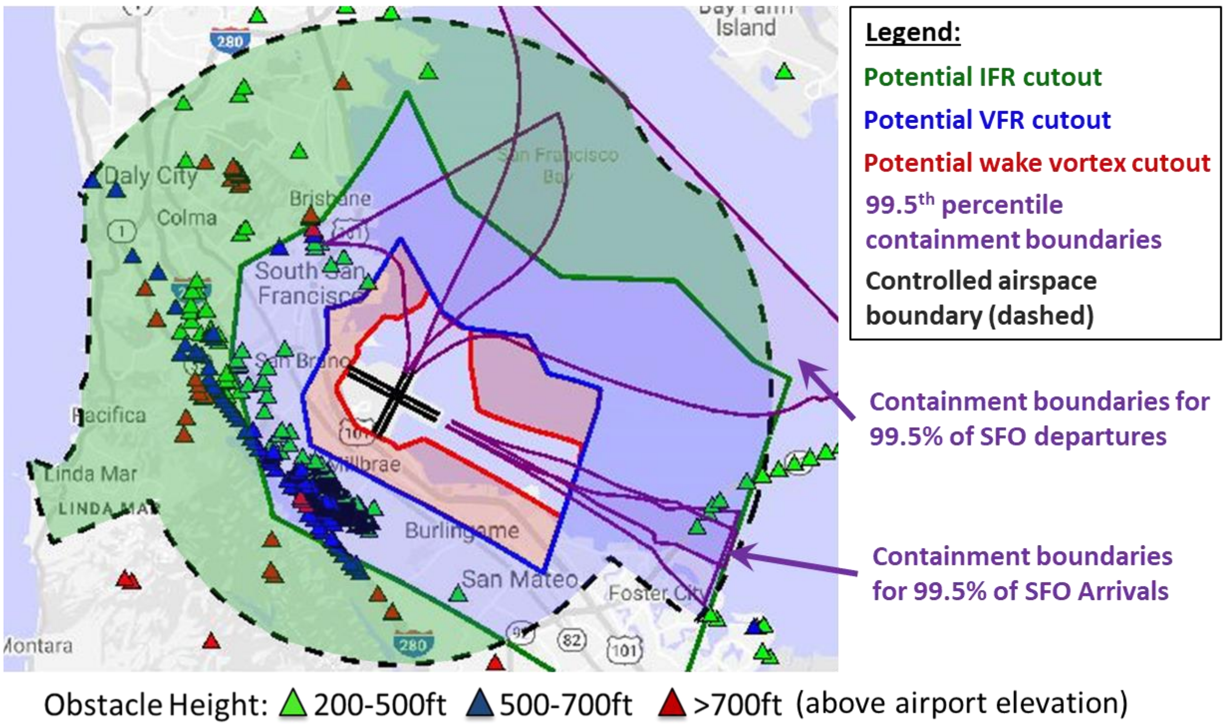


Fig. 56 Airspace cutout opportunity at SFO in a low wind, west flow pattern (83% frequency).

7.4.6 Sensitivity of Cutout Development to Conventional Aircraft Flight Dispersion

The dispersion of conventional aircraft on approach and departure procedures impacts the airspace available for UAM cutouts. Departure procedures display greater dispersion (i.e., containment boundary width) than arrival operations; this trend is displayed on the left of Fig. 57. Furthermore, dispersion varies significantly between the three airports as shown on the right of Fig. 57. The floor altitudes of the boundaries are more closely correlated between the airports except for departures at BOS where the floor altitude rises more slowly than at the other airports.

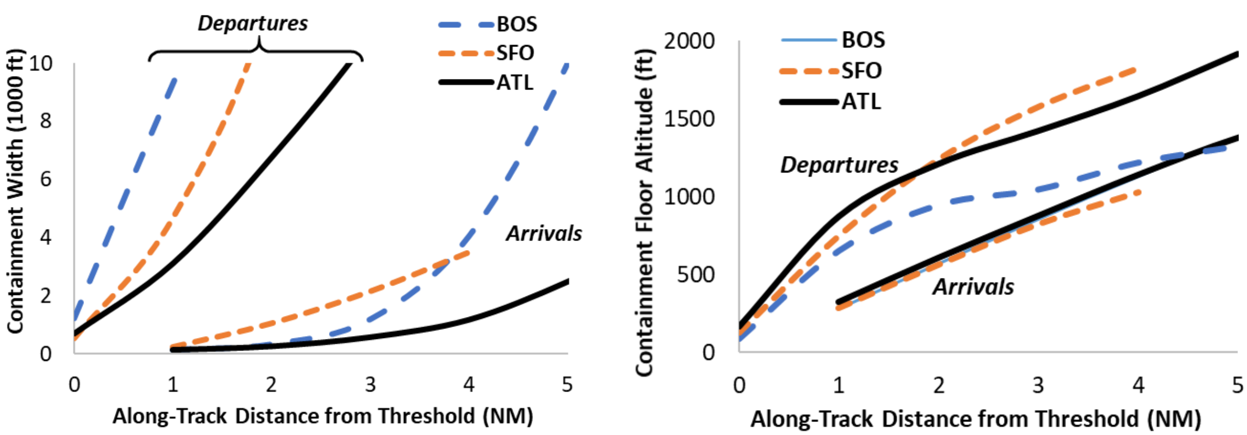
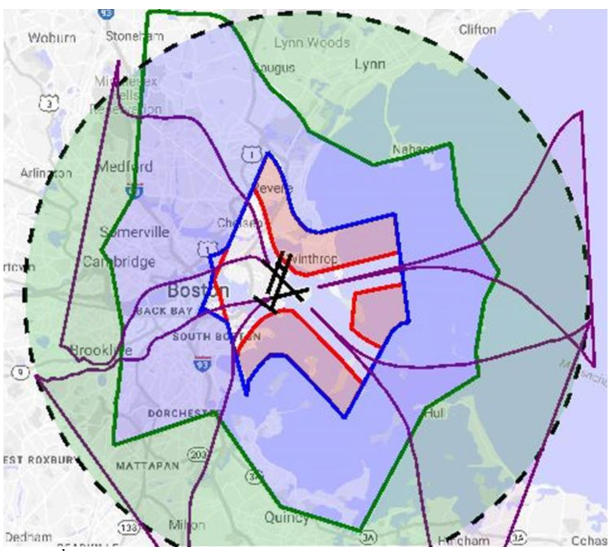


Fig. 57 Comparison of 99.5th percentile containment boundary properties for transport and regional aircraft flights.

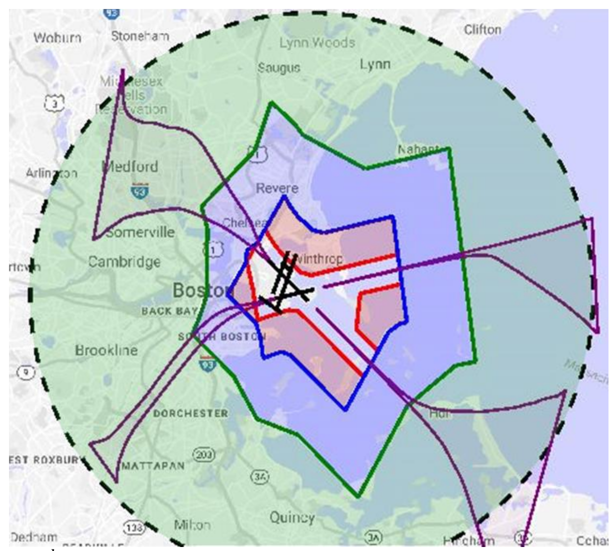
Airports with greater dispersion of conventional flights reduce the airspace that is available for the integration of UAM through the development of cutouts. Factors that may decrease the dispersion of flights at an airport include the use of PBN procedures, the use of simultaneous operations on parallel runways, and a higher percentage of large transport aircraft in the fleet mix of the conventional operators [137]. As displayed in Fig. 49, the top 0.5th percentile of flights accounts for a significant proportion of the dispersion, and the top 5th percentile accounts for the majority of the dispersion near the airport. Ref. [137] presents further analysis of conventional flight dispersion at the three case study airports.

Although this thesis assumed that large aircraft operations will not be adjusted to support the integration of UAM, Fig 58 displays how the potential for airspace cutouts would be impacted at BOS if the 95th percentile conventional operation was considered instead of the 99.5th percentile.

While the lateral extent of the departure containment boundaries is quite visibly reduced in Fig 58, the more significant influence on airspace cutout potential is the increase in the containment floor altitude for departures (i.e., climb-out gradient). The heightened containment floor altitude results in an increase in the size of potential IFR cutouts from 50% to 72%. The changes to the other types of cutouts are marginal.



99.5th Percentile Containment of Conventional Ops.



95th Percentile Containment of Conventional Ops.

Fig 58. Comparison of airspace cutout opportunities with different probabilities of interaction with conventional aircraft at BOS in a northwest flow pattern.

7.5 Conclusion

This chapter evaluated the allocation airspace to procedurally segregated cutouts to enable high-volume UAM operations within controlled-airspace near airports. UAM flights may occur in cutouts (initially under VFR only, but perhaps ultimately under IFR through the development of UTM-like capabilities) without limitations from controller workload or managed separation to conventional operations.

Through the modeling of 180 days of large and regional aircraft radar trajectories at three major airports, this chapter evaluated the potential benefits of developing airspace cutouts for UAM. The development of static airspace cutouts that provide VFR radar separation to 99.5% of conventional arrivals and departures in any runway flow pattern was shown to release up to approximately 75% of the surface-level controlled airspace to UAM at three case study airports. The deployment of dynamic cutouts, which are turned on or off based upon airport flow configuration, provided additional benefits at ATL and BOS.

Static airspace cutouts developed with IFR separation minima provide marginal benefits at BOS and ATL, but may reduce the amount of surface-level controlled airspace by nearly 50% at SFO. Dynamic IFR cutouts provide larger benefits for some airport flow configurations, but are challenged by the complexity of implementation. While UAM aircraft could not currently operate in an airspace cutout under IFR, future development of new ATC concepts and systems such as the NASA UTM project may support IFR UAM flights within IFR cutouts.

Based upon these findings, airspace allocation to cutouts appears to be a promising approach to minimize the airspace and surface locations where the scale of UAM flights may be restricted by ATC, especially as a result of controller workload.

The remaining two chapters of this thesis address a number of lingering questions concerning the influence of ATC on UAM scaling. Chapter 8 proposes procedures to support UAM flights to and from airports (and their immediate surroundings) where airspace cutouts are not feasible. Approaches to support IFR operations to airports or TOLAs that do not fulfill standard radar separation are also presented.

Chapter 9 evaluates the impact of the ATC constraint on UAM scaling across 34 cities in the United States. The effectiveness of the airspace cutout concept is evaluated at many more airports in these cities. Furthermore, the methodology developed in this chapter is enhanced. First, the potential for cutouts is evaluated with respect to all airports in a metropolitan area, rather than just the primary airport as conducted in this chapter. Second, the value of cutouts is partially dependent on what resides beneath the cutout. A cutout over open water may not be as valuable from a market perspective as a cutout over a city center. Therefore, instead of estimating the value of cutouts based upon the percentage of controlled airspace that is released, Chapter 9 evaluates the value of cutouts based upon access to potential UAM customer demand.

8 Supporting UAM Operations in Close Proximity to Airports

While airspace cutouts potentially support UAM access to a significant proportion of controlled airspace without ATC interaction and associated scaling limitations, cutouts cannot support UAM flights directly to an airport or its immediate vicinity due to minimum separation requirements from conventional operators. To access these areas, notionally shaded red in Fig. 59, alternative integration strategies are necessary for UAM that enable reduced separation minima to be applied.

This chapter investigates how existing arrival and/or departure procedures could be directly utilized or adapted to support high-volume, IFR or VFR UAM flights in close proximity to airports. Helicopter and small aircraft flights are first reviewed to establish baseline concepts for airport integration that were previously deployed.

Next, five operating schemes for UAM are distinguished by how closely a TOLA may be located to an airport's active runways and the relative angle between UAM flight paths and conventional aircraft operations. Fourteen arrival and departure procedures are evaluated for their ability to support simultaneous and non-interfering UAM flights in one or more of the operating schemes. Finally, the implementation of the most promising integration concepts is evaluated through case studies at Boston, Atlanta, and San Francisco international airports.

Enabling access to commercial airports may be critical for the scaling of near-term UAM systems. Initial market studies indicate that services to, from, or between (i.e., transfers) major airports represent a substantial proportion of the near-term market for UAM [5,6]. Furthermore, commercial, GA, or military airports are frequently located near densely populated metropolitan areas and may conflict with desired UAM operations and TOLA locations. Finally, strategies to support IFR UAM access to commercial airports may also support simultaneous IFR operations at closely-spaced TOLAs; this capability was identified as a critical requirement to increase TOLA IFR throughput capacity in Chapter 5.

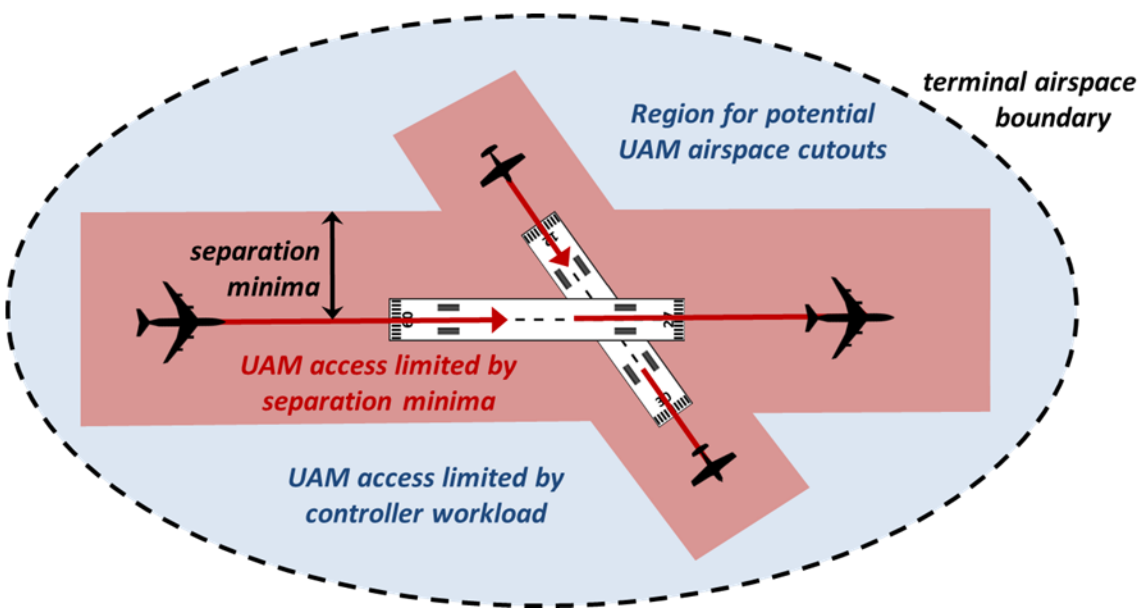


Fig. 59 Simultaneous and non-interfering UAM access to the red region requires an alternative approach to airspace cutouts which may only be developed in the blue region.

8.1 Review of Historic UAM-Like Operations Near Airports

Historic helicopter and small aircraft operations at major airports provided initial insight into integration strategies for UAM.

Chicago Midway and O'Hare airports each supported approximately 50,000 helicopter operations in 1960 [69]. The FAA developed a number of novel strategies at the time to handle this volume of helicopter operations. These strategies included:

- developing helicopter TOLAs that were located away from the active runway(s),
- designing helicopter routes that avoided conflict with fixed-wing arrival and departure procedures,
- authorizing bi-directional travel on helicopter routes with a 500 ft lateral offset from the centerline,
- assigning a dedicated controller and radio frequency for helicopter operations, and
- reducing the separation minima between VFR helicopters as well as between an IFR fixed-wing aircraft and a VFR helicopter.

Despite these strategies, high-volume helicopter operations at Midway and O'Hare were restricted to visual meteorological conditions (VMC). No helicopter operator at the time was certified to fly under IFR, and the IFR separation minima were not compatible with the helicopter routes and TOLAs. Interestingly, an FAA ATC specialist involved in these operations noted at the time [69]:

> *We recognize that the separation applied to the higher speed fixed-wing aircraft is excessive when applied to helicopters. The present state-of-the-art of Air Traffic Control, however, will not permit the luxury of separation standards for different classes of aircraft, as long as these aircraft are inter-mixed in the same airspace environment.*

Two decades later, Ransome Airlines pioneered STOL aircraft operations to the ends of inactive runways (i.e., "STUB" runways) [143]. This strategy did not require new infrastructure or controllers. The airline arrived at airports without interfering with conventional flights through specially designed routes, steeper approach glideslopes, and by holding short of conventional arrivals on the crossing runways during landing. Separation was managed visually by the Ransome pilots, and the frequency of operations was not high enough to trigger controller workload restrictions. For IFR operations, however, the airline was restricted to the use of conventual procedures and infrastructure.

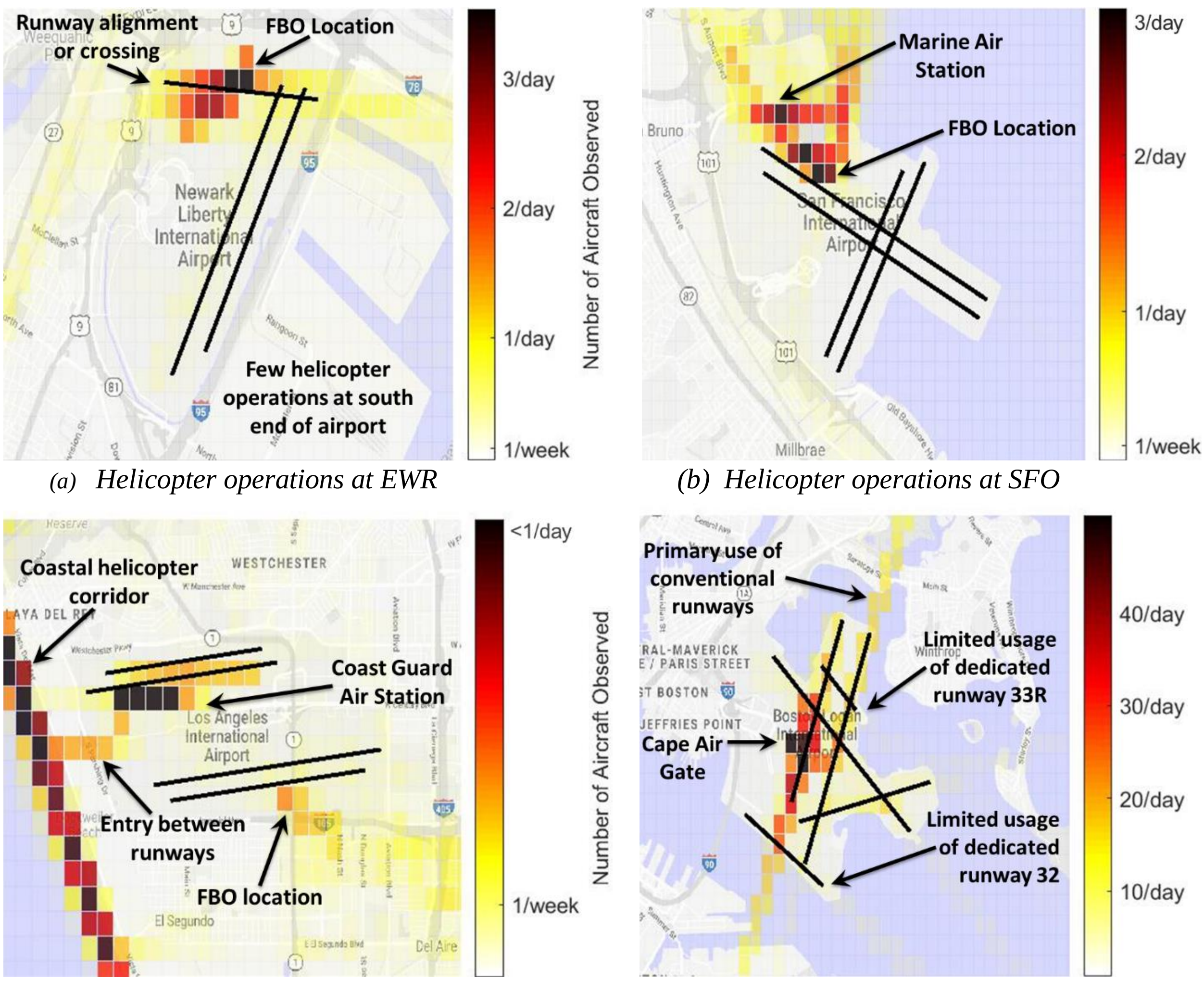
These historic operations reinforce the assumption that UAM aircraft must not interfere with conventional fixed-wing operations at airports. Furthermore, neither of these examples enabled high-volume IFR operations near airports. Addressing this knowledge gap is, therefore, a focus of this chapter.

8.2 Review of Current UAM-Like Operations Near Airports

According to the FAA Air Traffic Activity Data System (ATADS), between 2016 and 2018 the 30 largest airports in the U.S. supported an average of 48 GA arrivals or departures per day. Although this scale of operations is lower than those anticipated for UAM, the ATC strategies currently used to manage these flights represent a baseline integration approach.

As such, radar tracking data for GA and helicopter flights at Boston (BOS), Newark (EWR), Atlanta (ATL), Los Angeles (LAX), and San Francisco (SFO) international airports were assessed to identify the airfield infrastructure and flight paths used by GA and helicopter operators. A detailed analysis of each airport is presented in Appendix C and summarized below.

Fig. 60 displays heat maps of UAM-like operations below 1000 ft AGL at four airports. The majority of helicopter operations at ATL, LAX, and SFO fly directly to helipads or aprons located at the fixed base operator (FBO); these flights do not cross the runways or interact with the conventional approach and departure paths. In comparison, helicopter flights at EWR and BOS are primarily conducted to, from, or overtop the runways.



(a) *Helicopter operations at EWR*

(b) *Helicopter operations at SFO*

(c) Helicopter operations at LAX

(d) GA and Part 135 commuter operations at BOS

Fig. 60 Heat map of UAM-like operations below 1000 ft AGL for 180 days of radar tracks.
Note that the heat map scales are different in each sub-figure.

In Fig. 60, GA fixed-wing aircraft and commuter operations share the conventional runways and procedures at nearly all airports. The exception is at BOS where two independent runways (33R and 32) exclusively support small aircraft. These runways are limited to use in one wind pattern for VFR operations only, however, resulting in low utilization as shown in Fig. 60(d).

Helicopters provide greater flexibility in approach and departure path design than fixed-wing aircraft as displayed at SFO and LAX in Fig. 60(c) and (b), respectively. Furthermore, ATC policies afford a number of special allowances to helicopters. These allowances reduce weather or separation minima and authorize different procedures than fixed-wing vehicles may use. These allowances are predicated upon the unique performance characteristics of the helicopter including:

- <u>Reduced approach speed and/or hovering</u> which increases the time to conflict for a given separation distance and reduces the minimum turning radius. This capability enables helicopters to utilize reduced separation and visibility requirements in some situations.
- <u>Reduced ground roll</u> may increase margins for runway overrun or adjacent runway penetration, create opportunities to limit wake vortex encounters, or provide greater flexibility for airfield infrastructure siting in both movement and non-movement areas.
- <u>Flexible glideslopes</u> may increase vertical separation to aircraft on adjacent procedures as well as enable approach or departure operations in closer proximity to surface obstacles.

Some VTOL and STOL UAM aircraft are anticipated to exhibit performance characteristics similar to helicopters. However, it is unclear if these new vehicles will ultimately be classified as helicopters or fixed-wing aircraft. Considering this uncertainty, this chapter evaluates UAM integration near airports for aircraft of both classifications.

8.3 UAM Operating Schemes At or Near Airports

To evaluate UAM services at or near an airport, a framework for potential operations and TOLA locations was developed. Five operation schemes are represented in the framework based upon the distance and orientation of the UAM TOLA with respect to the airport's runways and flight procedures. As displayed in Fig. 61, each scheme has a unique region in which UAM TOLAs may be sited. TOLAs within each region experience similar procedure design and operational restrictions.

The bases for the parsing of the schemes were either a change in the type of separation minima that was required between UAM and conventional aircraft, or a change in the controller responsibilities required to manage the operation. Each scheme is summarized below:

- <u>Mixed-Use Operations</u>: UAM aircraft operate on the same runway as conventional aircraft. This requires a controller to sequence UAM aircraft with conventional aircraft to assure separation. Wake vortex separation is generally the driving constraint for runway throughput.
- <u>Closely-Spaced Operations</u>: UAM aircraft operate at TOLAs that are located close to the active runway(s). IFR UAM arrivals to closely-spaced TOLAs require three additional controllers to ensure separation (including wake vortex separation). VFR UAM arrivals do not require additional controllers, but may need to be sequenced with conventional aircraft for wake vortex separation requirements.

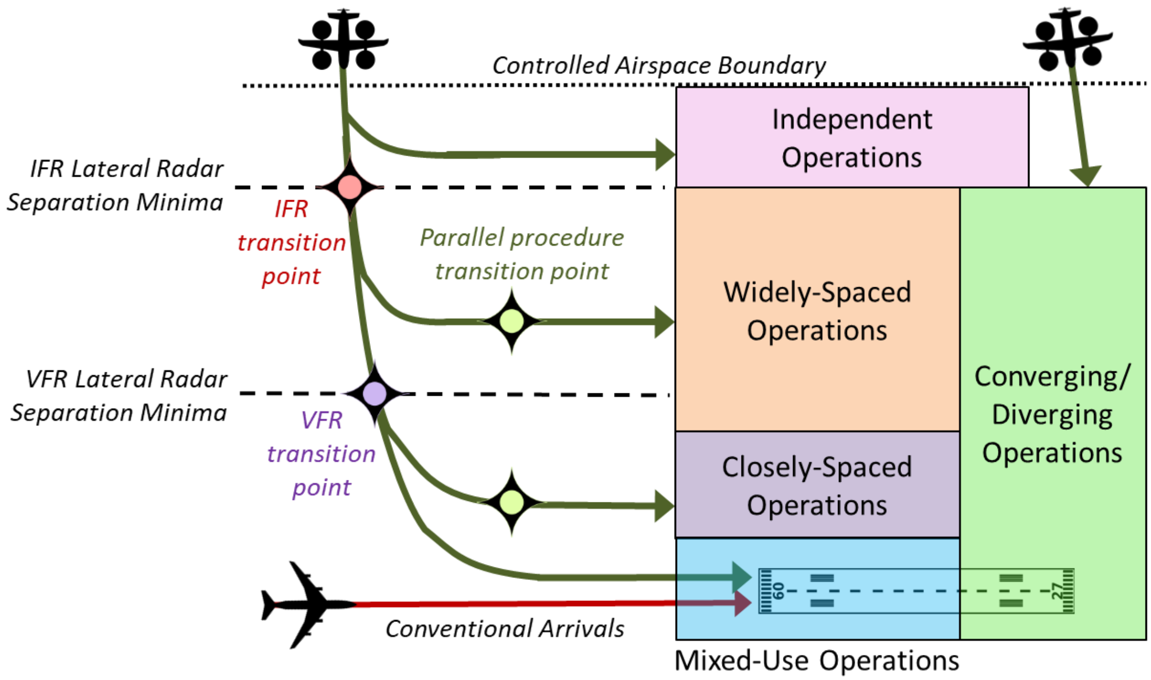


Fig. 61 Five operating schemes for UAM TOLAs located near airports.

- Widely-Spaced Operations: widely-spaced operations are differentiated from closely-spaced operations when separation is large enough from the active runway(s) to preclude the application of wake vortex minima. Widely-spaced UAM operations do not need to be sequenced with conventional aircraft. IFR UAM arrivals to widely-spaced TOLAs require one additional controller while VFR arrivals require no additional controllers.
- Independent Operations: UAM operations at TOLAs that are sited beyond the IFR lateral radar separation minima are fully independent from conventional flights in all weather conditions. A separate controller is required for the airport and the TOLA. The independent configuration matches the definition of the airspace cutouts presented in Chapter 7.
- Converging and/or Diverging Operations: TOLAs that support UAM flights that converge or diverge with conventional operations have alternative, and frequently reduced, separation requirements. Only one controller is required to manage both UAM and conventional aircraft operations in this scheme.

The three transition points indicated in Fig. 61 and listed below represent locations where the type of separation that is applied between UAM arrivals and nearby conventional aircraft must be changed.

1. IFR Transition Point: UAM arrivals that cross the IFR transition point may violate the IFR lateral radar separation minima to a conventional aircraft. To prevent a loss of separation, either a controller must sequence the flight to ensure temporal separation, the aircraft must either be established on a required navigation performance (RNP) approach procedure or another type of separation (i.e., SVFR, VFR, or visual) must be applied.

2. VFR Transition Point: VFR lateral radar separation is not met beyond the VFR transition point. Controllers must sequence aircraft or visual separation must be applied.
3. Parallel Procedure Transition Point: This transition point indicates the point at which UAM aircraft are established on the final approach. Once established, other forms of separation to an aircraft on a parallel procedure may be discontinued and procedure-specific separation requirements are applied.

Table 20 summarizes the existing approach and departure procedures used at airports. Each procedure exhibits different minimum runway spacing, workload, equipage (for either the aircraft or ATC), and aircraft performance as displayed in the table. The procedures in Table 20 are color coded to match their underlying operating scheme from Fig. 61. These procedures were used as a starting point to identify strategies for UAM integration near airports for each operating scheme.

Table 20. Overview of existing airport approach and departure procedures.

	Conventional Airport Procedure	Min. Runway Spacing (ft)	Minimum Controllers	Restrictions
Parallel Runways	Independent Parallel Approaches	9000	2	-
	Simultaneous Independent Parallel Appr.	4300	4	-
	Simultaneous. Close Parallel PRM* Appr.	3000	4	PRM surveillance system required
	Simultaneous Dependent Parallel Appr.	2500	2	same approach speeds required
	Independent Parallel Departures	2500	1	-
	High Approach Landing System	1640	2	same approach speeds required
	Simultaneous Offset Instrument Approaches	750	4	same approach speeds required
	Dependent Closely Spaced Parallel Runways	700	2	same approach speeds required
	Independent Visual Approaches/Departures	700	1	not authorized in IMC
	Shared Runway Approaches or Departures	0	1	-
Non-Parallel	Simultaneous Converging Instrument Appr.	non-overlapping	2	restrictive design limitations
	Land and Hold Short Operations	overlapping	1	not authorized in IMC
	Dependent Converging Instrument Appr.	overlapping	1	wake vortex dependent
	Independent Diverging Departures	non-overlapping	1	-

Widely Spaced Operations	Closely Spaced Operations	Mixed-Use Operations	Converging/Diverging Operations

**PRM – Precision Runway Monitor surveillance system*

8.4 Strategies to Support UAM Operations At or Near Airports

This section evaluates the feasibility of supporting UAM operations to TOLAs at or near airports in each of the five operating schemes presented in Fig. 61. The strategies discussed also support UAM operations to two TOLAs (as opposed to a TOLA and an airport).

8.4.1 Operating Scheme 1: Mixed UAM and Conventional Flights on a Shared Runway

While this concept is a natural starting point for UAM integration at airports as it does not require new infrastructure investments, the mixing of UAM and conventional operations presents a number of challenges including:

- close proximity of UAM flight to wake vortices generated by large aircraft,
- interaction of UAM and conventional aircraft on shared taxiways and runways, and
- heterogeneous aircraft performance (approach speed, ground roll, etc.)

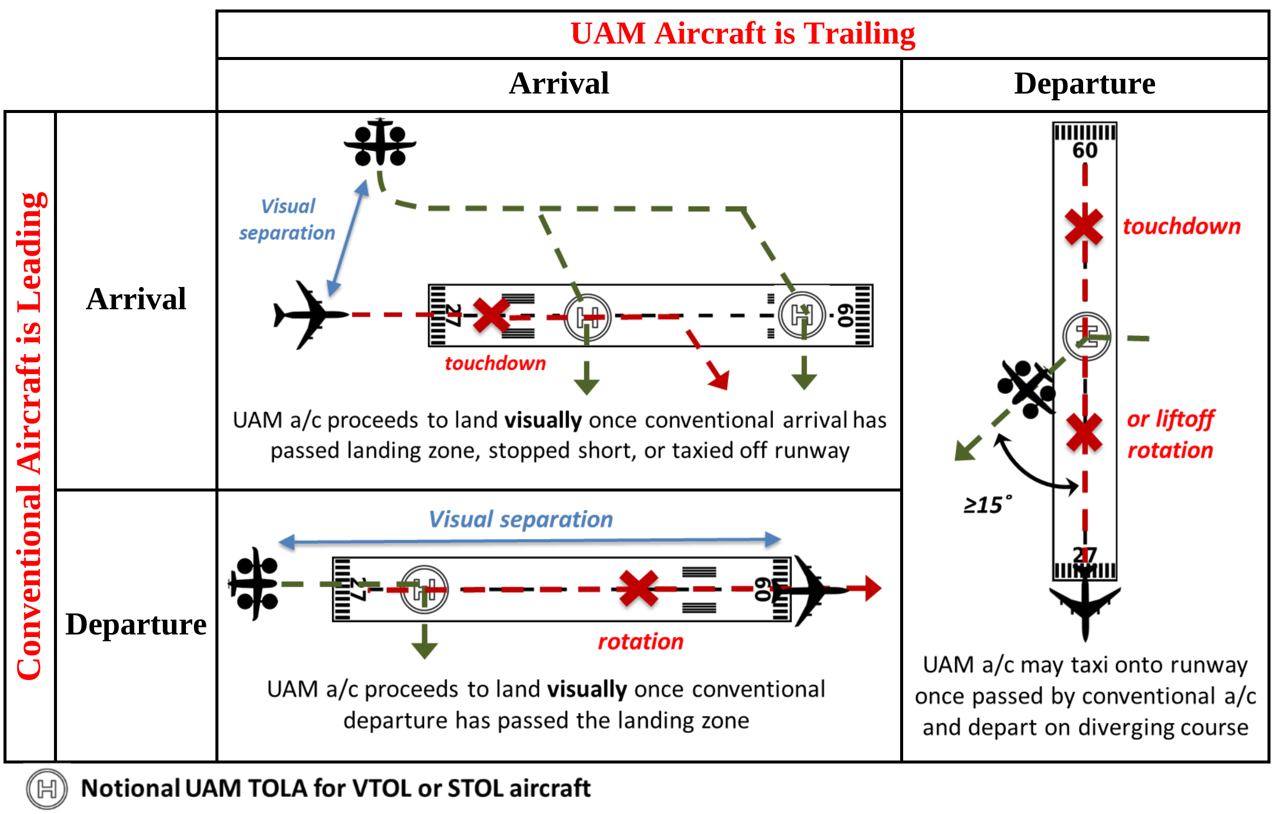
Furthermore, UAM flights must be interspersed between the conventional flights so as not to reduce conventional flight throughput. Separation minima, and especially wake vortex requirements, generally limit small aircraft operations behind larger preceding aircraft.

Despite these limitations, UAM aircraft operating under VFR, especially if certified as helicopters, may use visual separation to mitigate a majority of the wake vortex separation requirements and operate in-between conventional operations. However, IFR UAM operations would reduce conventional aircraft throughput on shared runways as wake vortex separation could not be relieved.

8.4.1.1 VFR Mixed Aircraft Operations

Table 21 displays strategies to support minimally interfering UAM operations on a shared runway with conventional aircraft. As a result of wake vortex requirements, the critical operating condition for throughput is UAM arrivals or departures behind prior large aircraft operations. Within and below Table 21 separate integration strategies are presented for four "modes" that describe the sequence of arrivals and departures. The four modes are a conventional arrival or departure followed by a UAM arrival, and a conventional arrival or departure followed by a UAM departure.

Table 21. Strategies for minimally interfering mixed UAM operations on shared runways.



Conventional Arrival – UAM Arrival Mode

Wake turbulence effects behind large aircraft challenge UAM aircraft operations on mixed-use runways. To minimize these effects UAM aircraft should touch down on the runway beyond the touchdown point of the previous arrival. UAM vehicles should also arrive on a steeper glideslope behind the larger aircraft or approach the runway from the side to avoid wake interactions [144]. Finally, UAM pilots would need to apply visual separation to reduce extensive wake vortex separation applied by controllers [108].

A UAM aircraft classified as a helicopter may land on the runway as soon as the prior arrival passes the desired landing zone. If the UAM aircraft is classified as a fixed-wing, however, then it must wait until the prior arrival has cleared the runway. Either aircraft type could also land on the departure end of the runway once the previous arrival has come to a stop on the runway [108].

Analysis of radar tracking data found that approximately 40% of arrivals to BOS occurred with inter-arrival times of less than 120 s. Medium runway occupancy time (ROT) for large aircraft at BOS was found to be 46 s. Therefore, UAM aircraft may have 74 s or less for final approach, landing, and clearing of the runway before the next conventional arrival is at the runway threshold.

Conventional Departure – UAM Arrival Mode

UAM arrivals should land behind conventional departures at a point before their rotation occurred in order to minimize wake vortex interactions. If classified as a helicopter, UAM aircraft may land as soon as the prior flight crosses the desired touchdown point. When classified as a fixed-wing, UAM aircraft must wait to land until the previous aircraft is airborne and at least 6000 ft down the runway (or cleared the runway end) during the daytime or has cleared the runway end at night.

Conventional Departure – UAM Departure Mode

Slotting UAM departures in between conventional departures may be achieved through course divergence. Typically, small aircraft require up to 180 s of time between the departure of a prior large aircraft and the beginning of their ground roll in order to reduce wake vortex interactions. However, if the UAM ground roll is sufficiently short then the aircraft may depart from conventional runways at a divergence angle of at least 15˚ from the centerline without having to wait a specified period of time [108]. Diverging departures provide an alternate means to mitigate wake vortex interactions.

Conventional Arrival – UAM Departure Mode

A diverging course may also support UAM departures behind conventional arrivals. Following the prior aircraft's landing, a UAM aircraft may taxi onto the runway and depart from a location beyond the conventional aircraft touchdown point.

8.4.1.2 IFR Mixed Aircraft Operations

No plausible integration concepts were identified under current regulations to enable IFR arrivals to shared-used runways without reducing conventional aircraft throughput. Pilot or tower-applied visual separation may not be applied to IFR operations meaning the same radar and/or wake vortex separation minima are applied to UAM aircraft as to conventional flights. UAM IFR departures, on the other hand, may be supported through the same diverging course procedure as presented for VFR departures.

8.4.1.3 *UAM Throughput on Shared Runways*

The throughput of UAM operations from shared-used runways is limited in terms of the number of slots available in-between conventional aircraft operations. In order to increase UAM throughput, the number of operations achieved per available slot may be increased. Three high-level approaches to achieve this are proposed below.

First, VFR UAM operations may simultaneously arrive or depart either 200 ft or 300 ft laterally from one another when classified as helicopters or fixed-wing aircraft, respectively [108]. Multiple simultaneous UAM operations spaced along the length of the runway could therefore be conducted within each conventional aircraft inter-arrival or inter-departure slot.

Second, UAM aircraft could arrive or depart in formations of aircraft. Formation flights are not currently authorized for passenger carrying operations under 14 CFR §91.111. However, advanced navigational equipment with more automated flight management systems and/or vehicle-to-vehicle communications may increase the safety of these operations. Large-scale formation landings and departures of small aircraft are demonstrated during the mass Bonanza arrival to the Oshkosh airshow each year.

Third, reduced inter-arrival spacing may increase throughput. The FAA currently authorizes some airshows to use inter-arrival spacing for GA aircraft that is reduced from 3000 ft to 1500 ft [145].

8.4.2 Operating Scheme 2: Closely-Spaced Operations

The use of UAM TOLAs that are closely spaced to conventional runways can increase throughput at airports or their surrounding communities by enabling independent UAM and conventional operations. Fig. 62 notionally displays the closely-spaced operating scheme. Both VFR and IFR approaches may be supported down to the same separation minima.

The closely-spaced scheme assumes UAM aircraft are landing and departing from TOLAs that are parallel to the nearby conventional runway. UAM operations at TOLAs that converge or diverge with the conventional runways, even if closely-spaced to one another, represent a different operating scheme and are discussed in section 8.4.5.

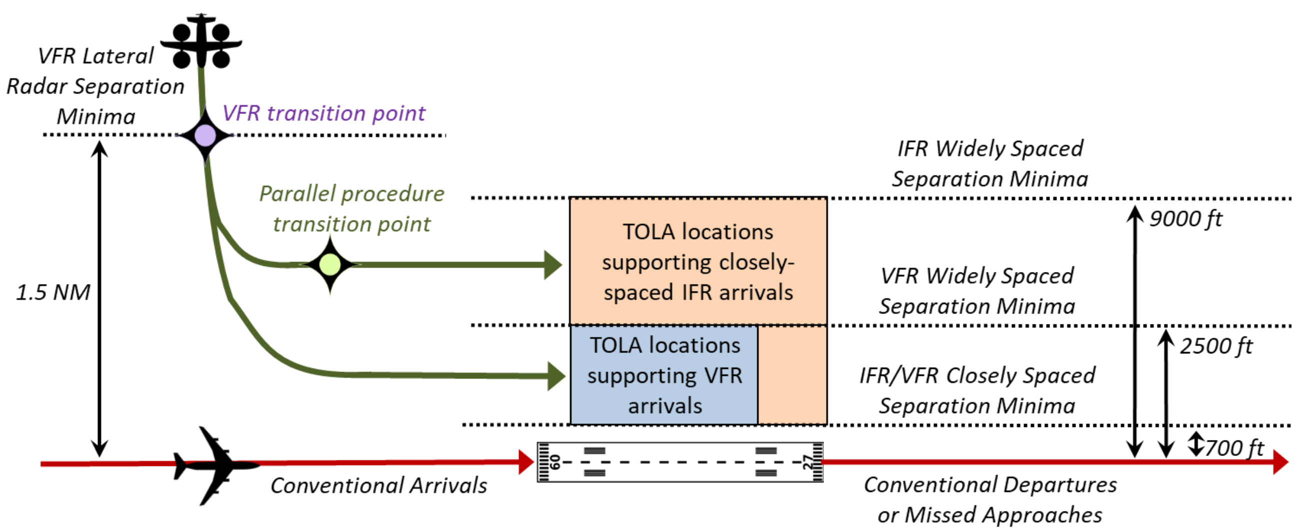
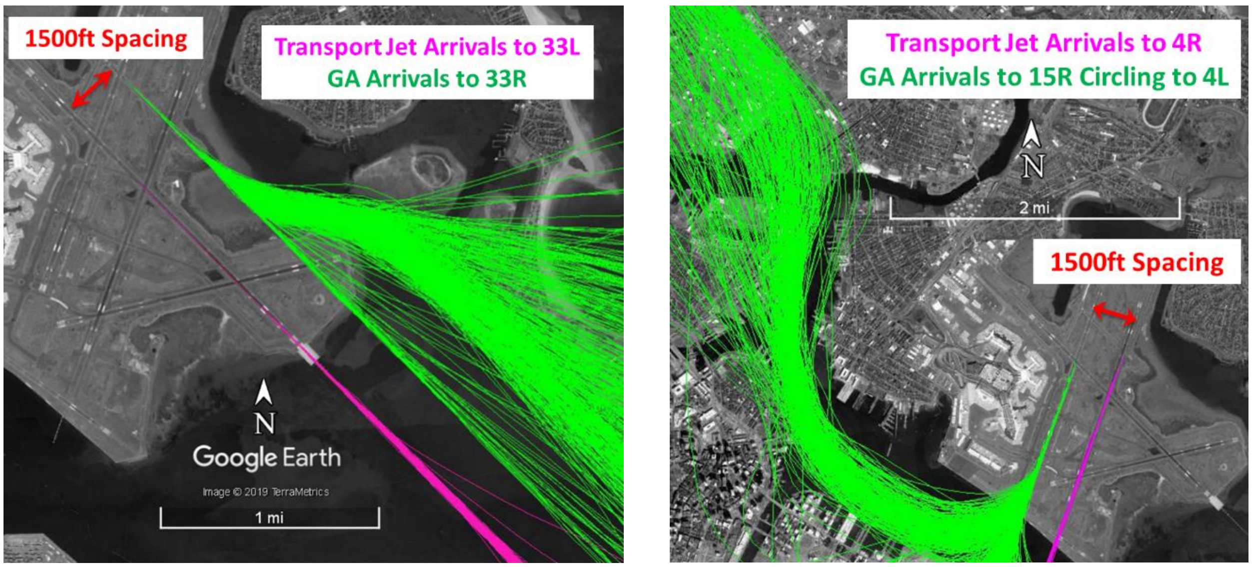


Fig. 62 Separation requirements for closely-spaced operations.

8.4.2.1 *VFR Closely-Spaced Operations*

Closely-spaced VFR arrivals may be conducted with lateral separation of 700 ft to 2500 ft from conventional flights. Visual separation by pilots or controllers is required. During closely-spaced arrivals, the smaller aircraft in the operation may not be passed by a large aircraft for wake vortex mitigation. The passing restriction requires controllers to sequence UAM arrivals representing additional workload and making TOLA operations dependent on the runway operations.

Fig. 63(a) displays VFR GA arrivals (green) to BOS runway 33R that are sequenced with transport jet arrivals (pink) to runway 33L. Fig. 63(b) displays VFR GA arrivals that circle from 15R onto 4L and intercept the final approach course close to the threshold. The second, circling procedure minimizes the impact of the passing restriction by shortening the length of time the small aircraft is parallel to the large aircraft.



(a) Straight-In Arrivals *(b) Arrivals Circling from Crossing Runway*

Fig. 63 Radar tracks for closely-spaced VFR arrivals at Boston.

Departure operations are more restrictive than arrivals for closely-spaced VFR operations from a throughput perspective. UAM aircraft may be required to wait multiple minutes behind conventional aircraft departures on runways that are spaced less than 2500 ft to allow for wake vortex dissipation.

It should be noted that UAM aircraft that are classified as helicopters may be exempted from the wake vortex separation requirement if they depart from a non-movement area of the airport or an area beyond the airport boundary. Non-movement areas include ramps and aprons (as well as ground-side infrastructure including parking garages). Air traffic controllers, subject to their personal judgment of the safety and reasonableness of the operation, may clear helicopters to depart or arrive at their "own risk" from these areas even if the vehicle is less than 2500 ft from simultaneously operating large aircraft ([108] – section 3-11-2).

Due to the reliance of helicopter operations from non-movement areas on subjective controller judgments, this type of procedure was not considered further in this thesis. Operations of this type are an area of potential future research for UAM airport integration.

8.4.2.2 IFR Closely-Spaced Operations

Closely-spaced IFR operations occur at TOLAs separated by less than 9000 ft but more than 700 ft from one another or a conventional runway. Multiple current procedures to support closely-spaced IFR operations were highlighted in purple in Table 20.

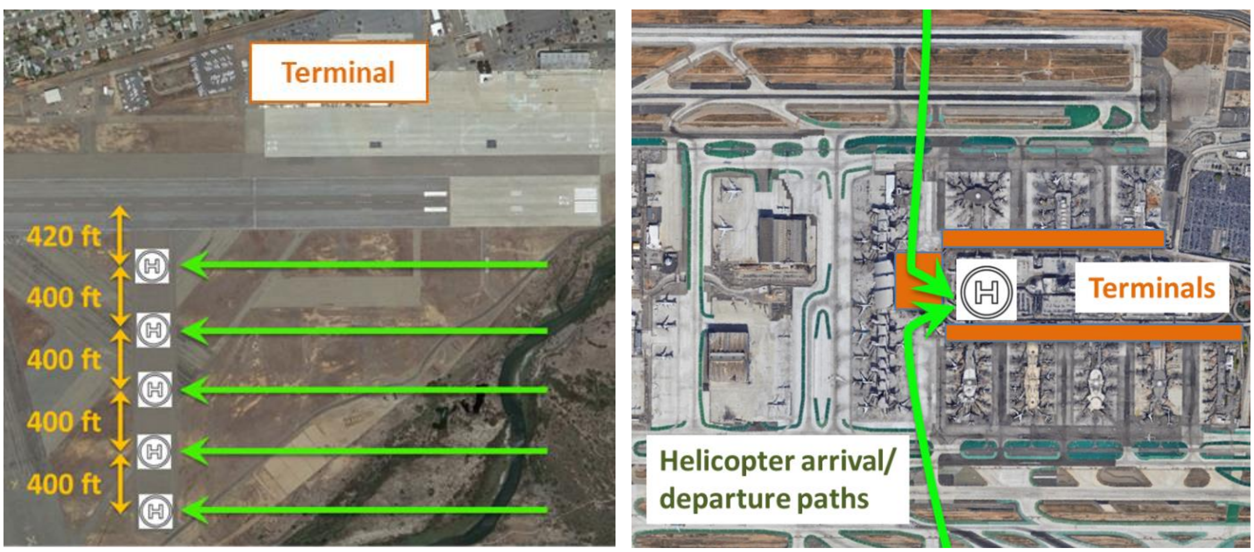
Simultaneous UAM arrivals separated by less than 2500 ft from conventional flights require precise lateral and longitudinal spacing between the aircraft. To achieve this, extensive sequencing and trajectory conformance monitoring is conducted by controllers increasing their workload per flight. Furthermore, UAM aircraft would be required to operate at similar approach speeds as the large aircraft during these procedures which may not be feasible from a performance standpoint.

UAM IFR arrivals separated by 3000 ft to 9000 ft do not require the precise sequencing of aircraft or similar approach speeds. However, controller workload remains a potential scaling constraint as four controllers are required to support these arrivals procedures.

Finally, IFR arrivals to any closely-spaced TOLA must pass through the IFR transition point indicating that lateral radar separation is not sufficient. Traditionally, IFR vertical separation is applied until the flight is established on the final approach at the parallel procedure transition point. However, properly equipped UAM aircraft may leverage established on RNP (EoR) capabilities as an alternative form of separation to reduce the controller workload of this transition. EoR is not authorized for runways spaced less than 3000 ft.

8.4.2.3 Closely-Spaced TOLA Siting and Terminal Access

The primary benefit of the closely-spaced operating scheme is the relative ease with which a UAM TOLA may be sited near the airport terminals or in communities next to the airport. Helicopters provide the greatest flexibility for closely-spaced VFR integration as they may operate from non-movement areas or even from helipads co-located with terminals. Fig. 64 displays two closely-spaced airport integration examples for helicopter operations.



Naval Outlying Landing Field Imperial Beach *Los Angeles International Airport*

Fig. 64 Existing closely-spaced VFR TOLA examples for helicopter operations.
Map data © 2019 Google.

8.4.3 Operating Scheme 3: Widely-Spaced Operations

TOLAs must be located at least 9000 ft from conventional runways to support widely-spaced IFR arrivals, or 2500 ft for widely-spaced IFR departures and any VFR flight. Fig. 65 notionally displays the separation requirements and TOLA siting opportunities for widely-spaced UAM operations.

Widely-spaced infrastructure simplifies UAM integration near airports from an ATC standpoint, especially during IMC. The widely-spaced operating scheme may relieve requirements to separate and sequence UAM aircraft with conventional flights when EoR technologies are used. Furthermore, widely-spaced operations do not require wake vortex separation, additional controllers for trajectory conformance monitoring, or the use of advanced radar systems. However, widely-spaced TOLAs may be challenged to rapidly connect UAM passengers to the commercial terminals.

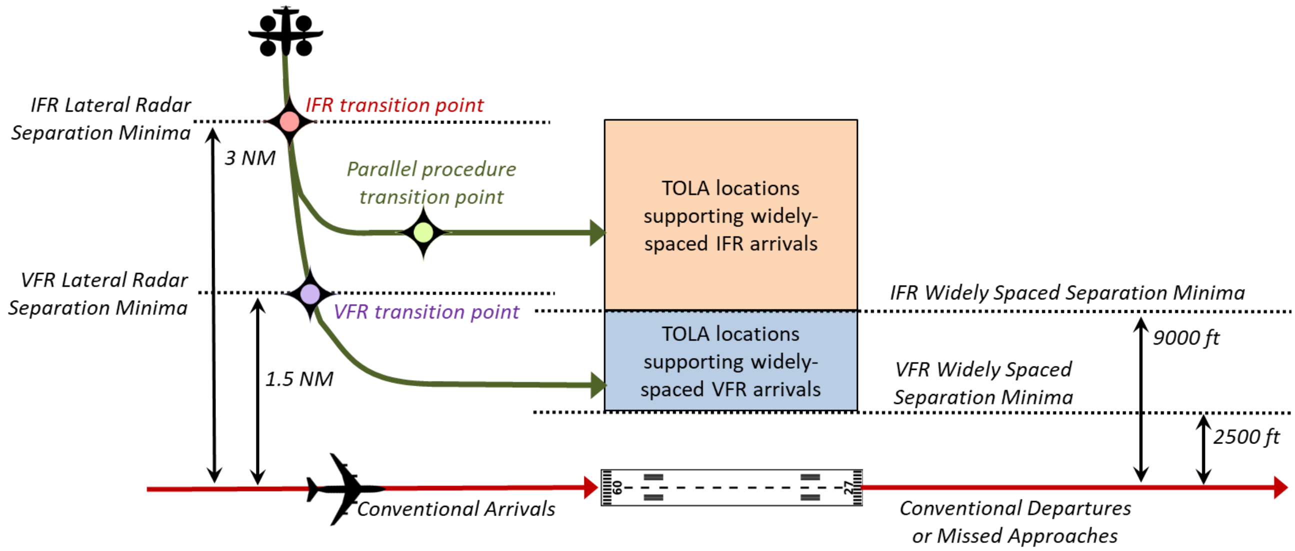


Fig. 65 Separation minima for widely-spaced operations.

8.4.3.1 TOLA Siting and Terminal Access

Widely-spaced TOLAs potentially present less utility to airports and communities near airports. First, the number of widely-spaced TOLAs that may be sited near airports is limited if 9000 ft of separation must be provided between each one as well as to the conventional runways. Second, terminal accessibility from the TOLA is reduced as it is located far away. Terminal accessibility is the time required for aircraft to taxi from the TOLA to the gate, and then for the passengers to travel from the gate to the conventional aircraft terminals (and vice-versa).

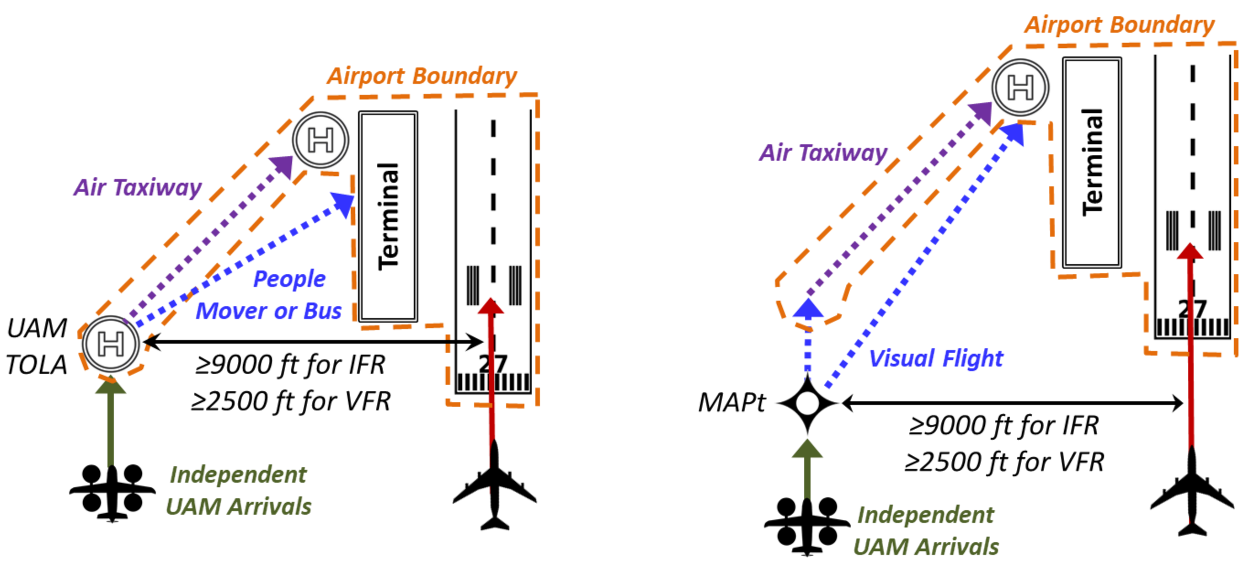
Terminal accessibility may be improved by increasing the speed of aircraft taxiing and passenger transfer. For example, people movers, buses, or on-demand car services enable rapid passenger transfers from remote gates, aprons, or terminals at many airports. Nice Cote D'Azur airport in France exemplifies this approach where a widely-spaced VFR heliport is located 4000 ft from the terminals beyond the furthest runway but has a dedicated bus system with a tunnel beneath the runways to provide rapid access to the terminals for passengers.

Air taxiing (and to a lesser degree hover taxiing) is also a promising approach to reduce taxi time for far-flung TOLAs. Air taxiing enables UAM aircraft classified as helicopters to fly at low altitudes and speeds over improved or unimproved surfaces (even water). An air taxiing helicopter is treated as a ground taxiing aircraft which negates airborne separation requirements. Air taxiing, therefore, decouples TOLA location from terminal accessibility.

There are two limitations for the use of air taxiing, however. First, air taxiing over long distances may challenge UAM aircraft performance from an energy or safety perspective, especially those concepts that are electrically powered. Second, air taxiing must occur *within the lateral bounds* of the airport property. Many airports, especially those near cities (such as Boston Logan or New York LaGuardia), may not have large enough land footprints to enable the siting of widely-spaced TOLAs within the airport boundary such that air taxiing could access the commercial terminal.

A Point in Space (PinS) approach may overcome the limitations of air taxiing. A PinS approach is flown to a missed approach point (MAPt) located at a specified distance above the surface with no physical TOLA infrastructure below. At the MAPt, the UAM flight transitions to visual flight *if the weather conditions permit* and continues to a gate. A PinS approach may support widely-spaced IFR arrivals to gates sited with the VFR separation minima without the new for new TOLA physical infrastructure (procedure design and CNS infrastructure is required).

Fig. 66(a) displays concepts for widely-spaced arrivals with air taxiing or surface transfer connections to the terminal. Fig. 66(b) displays the PinS concept to for widely-spaced arrivals. Section 8.5 provides examples for how either of these concepts may be implemented at large commercial airports.



(a) *Physical TOLA ConOps* (b) *Point in Space (PinS) ConOps*

Fig. 66 Concepts to provide increased terminal accessibility for widely-spaced TOLAs.

8.4.4 Operating Scheme 4: Independent Operations

The fourth operating scheme considers UAM arrivals and departures that never pass within the IFR or VFR lateral radar separation minima. TOLAs beyond these minima may operate independently from the airport and UAM aircraft may remain procedurally segregated from conventional flights. As such, the regions that support independent operations are candidates for airspace cutouts as discussed in Chapter 7.

The disadvantage of independent operations is the large separation required between TOLAs or between a TOLA and the airport. Providing three nautical miles between TOLAs for IFR operations would prevent multiple facilities from serving one metropolitan area. Furthermore, a three mile air taxi or PinS visual segment to connect the TOLA to the airport may not be authorized by ATC or feasible from an aircraft performance perspective.

8.4.5 Operating Scheme 5: Converging or Diverging Operations

The final ATC integration scheme for airports addresses UAM arrivals and departures at infrastructure that is at an angle to, or intersecting with, the conventional runways. Converging or diverging arrivals and departures provide a number of integration benefits for UAM.

First, diverging infrastructure enables simultaneous IFR or VFR departures from closely-spaced runways without the requirement to apply wake vortex separation. Second, independent converging arrivals may be conducted to closely-spaced or intersecting runways (or TOLAs) for VFR or IFR. Third, converging arrivals do not require additional controllers to monitor trajectory conformance.

Fig. 67 notionally displays the converging operation scheme. There are no differences between the regions where IFR and VFR converging TOLAs may be located. The specific procedures required to ensure separation and the safety of converging or diverging operations are introduced in the following sub-sections.

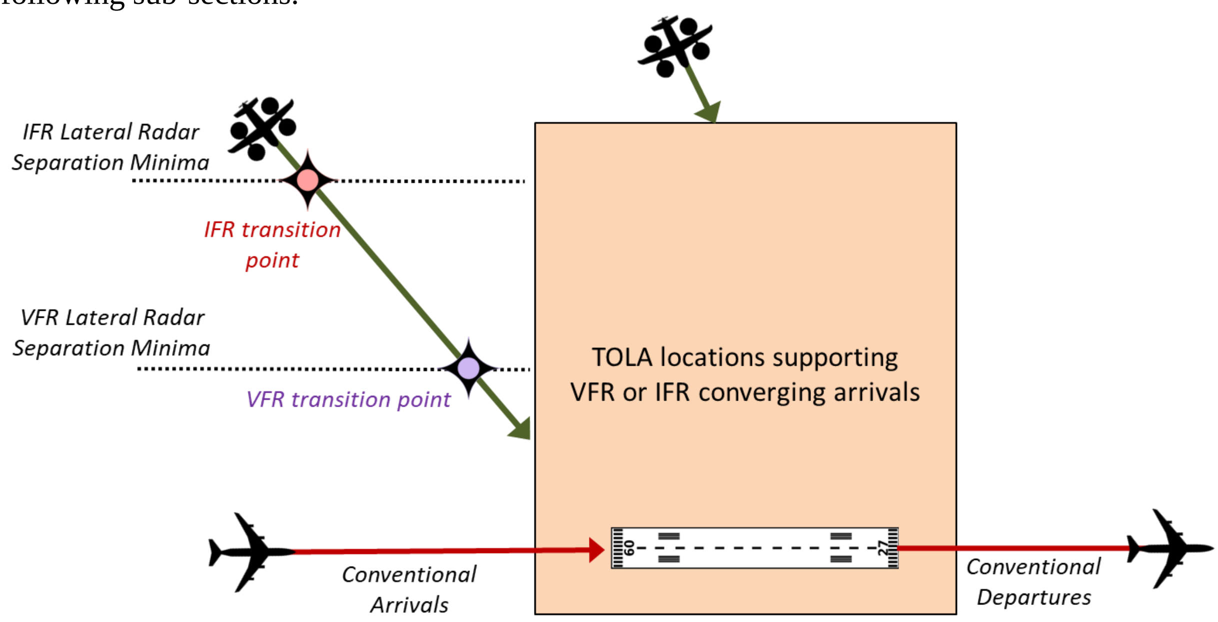


Fig. 67 Notional converging operations.

8.4.5.1 VFR Converging or Diverging Operations

Converging VFR arrivals to non-intersecting runways are achieved through visual separation. Sequencing and wake vortex separation are only required if flight paths cross, otherwise the operations may be handled as fully independent runways.

Land and Hold Short Operations (LAHSO) support simultaneous VFR operations on crossing (i.e., physically intersecting) runways. The advantage of LAHSO is it may enable UAM operators to land on existing crosswind runways without impacting conventional aircraft throughput or requiring independent controllers.

Finally, VFR or IFR departures that diverge from the conventional runways by at least 15˚ are exempt from wake vortex requirements; this enables closely-spaced departures for UAM.

8.4.5.2 IFR Converging or Diverging Operations

Simultaneous Converging Instrument Approaches (SCIA) enable UAM aircraft to land on a converging but non-intersecting runway without requiring coordination with conventional flights. Fig. 68 displays notional SCIA for UAM operations. To provide safety, the missed approach paths of the procedures do not overlap, lateral IFR radar separation is maintained between the flights until the MAPt, and the pilots are responsible to visually avoid one another in the case of a simultaneous go-around by both aircraft.

The primary limitation of SCIA for UAM airport integration is a design requirement to space the MAPt for each arrival procedures at least 3.0 NM from one another as displayed in Fig. 68. This requirement limits either the approach radial, decision height, or touchdown location that UAM aircraft can use. However, previous risk analysis of SCIA indicated that a reduction of the MAPt spacing has a limited impact on the safety of the operation even for conventional aircraft [146]. Furthermore, UAM aircraft with lower approach speeds, hover capability, or shallower glide slopes may enable closer MAPt spacing while maintaining and equivalent level of safety as SCIA operations by conventional aircraft.

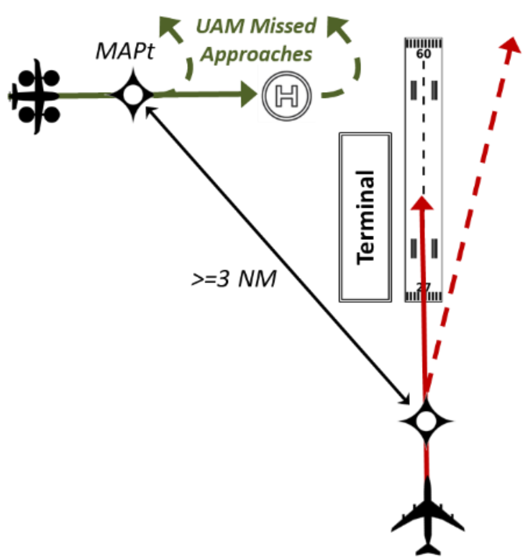


Fig. 68 Simulatenous Converging Instrument Approaches (SCIA) for UAM IFR arrivals.

As an alternative to SCIA, LAHSO could potentially be adapted to support IFR UAM arrivals. LAHSO currently provides safety through two means:

1. If the leading aircraft fails to hold short of the crossing runway, then the following aircraft conducts a go around to avoid potential conflict.
2. If the leading aircraft initiates a go around, then the pilot is responsible to ensure visual separation from the following aircraft even if it also conducts a go around.

These safety mechanisms may be enhanced by UAM aircraft performance capabilities, especially the reduced approach speed and ground roll of the aircraft. Furthermore, in a rejected landing situation a UAM aircraft may have new conflict avoidance options including to hover short of the crossing runway or execute a missed approach with a tighter, lower speed turn. If UAM aircraft are capable of providing these new performance capabilities then it may be possible to certify LASHO for IFR operations. Developing the safety case for such operations is a promising area for future research.

8.4.5.3 TOLA Siting and Terminal Access

A converging and diverging configuration may ease TOLA siting at or near airports. LAHSO enables UAM aircraft to use existing crossing runways. SCIA may enable IFR UAM flights to land at TOLAs in close proximity to the airport terminals. Diverging departures provide significant TOLA siting benefits for both IFR and VFR flights as they enable simultaneous departures from closely-spaced infrastructure without wake vortex separation requirements.

8.5 Case Studies of Promising Airport Integration Strategies

Four airport integration strategies show promise to support UAM operations in close proximity to airports under different weather scenarios. These strategies are:

- Diverging Departures: VFR or IFR departures from a TOLA with a divergence angle of 15° or more from the runway actively supporting conventional aircraft flights are considered to be independent from an ATC standpoint. There is no minimum separation distance between UAM TOLAs supporting diverging departures and other runways or TOLAs. However, the safety-areas of the TOLA and runway may not intersect.
- Converging Arrivals: converging arrivals enable the closest siting of independent TOLAs to an airport in either IMC or VMC. For VFR operations, LAHSO supports UAM arrivals to existing crossing runways. Converging VFR arrivals may also be conducted to an independent UAM TOLA located near the runways as long as aircraft flight paths do not overlap. For IFR operations, SCIA may enable arrivals to TOLAs near the terminals if relief to the 3.0 NM MAPt separation policy is authorized.
- Widely-Spaced PinS Arrivals: UAM aircraft may conduct simultaneous and independent IFR arrivals through a PinS that is widely-spaced from the airport (i.e., >9000 ft from conventional operations). Weather permitting, the UAM flight then transitions at the MAPt to a VFR converging arrival to a gate located at the airport or terminal.
- Widely-Spaced VFR Arrivals: If VFR converging arrivals are not possible, then VFR arrivals to TOLAs spaced 2500 ft from conventional runways followed by an air taxi segment to a gate located near the terminal is a promising alternative.

Each integration strategy was evaluated at Atlanta (ATL), Boston (BOS), and San Francisco (SFO) international airports. These three case studies utilized a similar approach to the airspace cutout analysis presented in Section 7.4.2.

Widely-spaced IFR PinS arrivals were modeled to require UAM aircraft operating at 300 ft AGL to maintain a minimum lateral and vertical separation of 9000 ft and 1000 ft, respectively, to the 99.5th percentile containment boundaries for conventional flights. Widely-spaced VFR arrivals required a minimum lateral and vertical separation of 2500 ft and 500 ft, respectively. Converging arrivals and diverging departures were considered potentially feasible within 2500 ft laterally and 500 ft vertically of conventional flights.

8.5.1 UAM Operations in Proximity to Atlanta International Airport

Fig. 69 displays three regions surrounding ATL where TOLAs may be sited for the four promising UAM airport integration strategies. ATL's terminals are indicated with a green box in Fig. 69, and the airport's runways are shown with black bars. The region where independent converging arrivals or diverging departures may be conducted is tinted red. The blue tinted region may support widely-spaced VFR arrivals. The green tinted region represents where widely-spaced IFR PinS arrivals may be conducted. Areas beyond the green boundary may support fully independent IFR or VFR UAM operations.

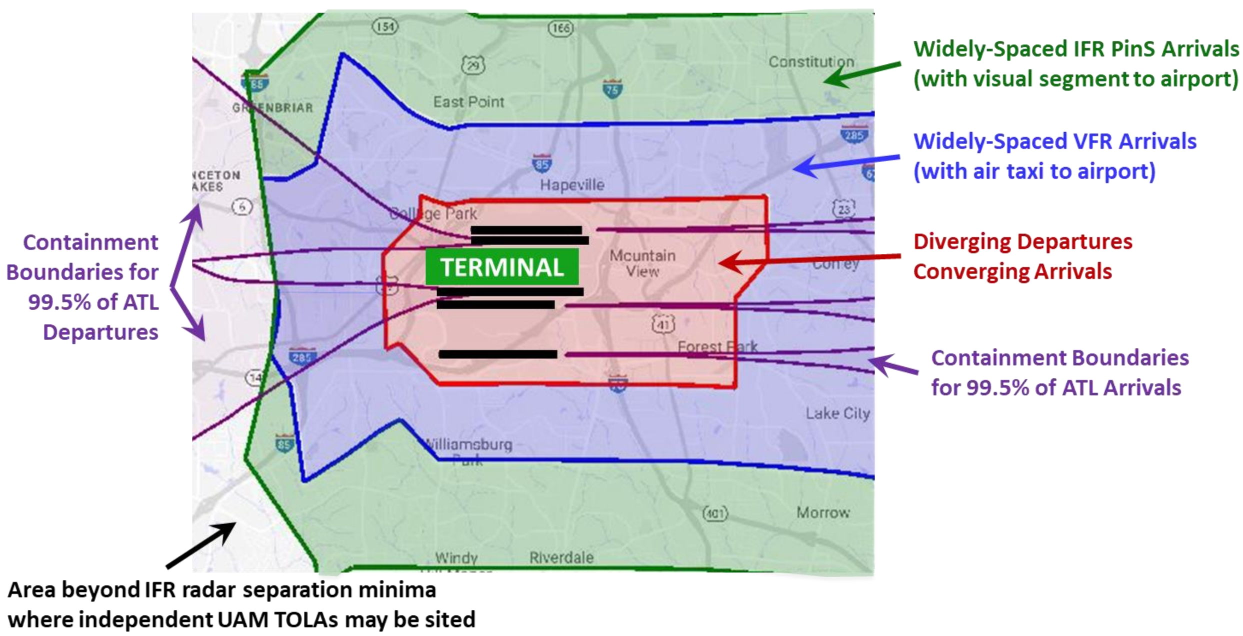


Fig. 69 Airport integration strategies at ATL for a west flow pattern (64% frequency).

IFR or VFR UAM flights may conduct converging and diverging operations to TOLAs located within or beyond the red region of Fig. 69. While converging operations could provide direct access to communities north or south of the airport, the ATL terminal is imbedded between parallel runways preventing converging or diverging UAM operations directly to the terminal. UAM aircraft could not cross over the runways or conventional flight trajectories without sequencing from controllers (or new traffic management automation). As a result, an alternative connection to the terminal (such as surface transportation or air taxiing) would be required from UAM TOLAs located either beyond the runways.

Widely-spaced VFR arrivals to the blue region are similarly limited by the imbedded nature of the ATL terminal. Widely-spaced TOLAs sited north or south the airport would require subsequent taxiing over the runway or a ground transportation segment to the terminal. Fig. 70 displays how a TOLA located 2500 ft north of ATL's north-most runway could support either widely-spaced VFR arrivals or converging/diverging operations. This TOLA is sited within the current airport boundary and an air taxi segment could be used, with sequencing, to cross the runways and access the ATL terminal.

Converging/diverging operations at a TOLA located one mile west of the airport may provide fully independent UAM access to the terminal. A TOLA in this location is beneath the ATL departure and missed approach paths for the west flow pattern and provides at least 500 ft of vertical separation to conventional flights overhead if UAM aircraft approach below 300 ft AGL. As displayed in Fig. 70, UAM aircraft arriving to a TOLA west of the airport may air taxi the remaining mile to a gate co-located at the terminal; this air taxi segment is not subject to separation minima. However, this TOLA location is not within the airport property boundary and an air taxi segment could not be conducted under current ATC policies. If ATL shifts to an east flow pattern, UAM could shift VFR arrivals to a TOLA located approximately a mile and half east of the airport as shown in Fig. 70.

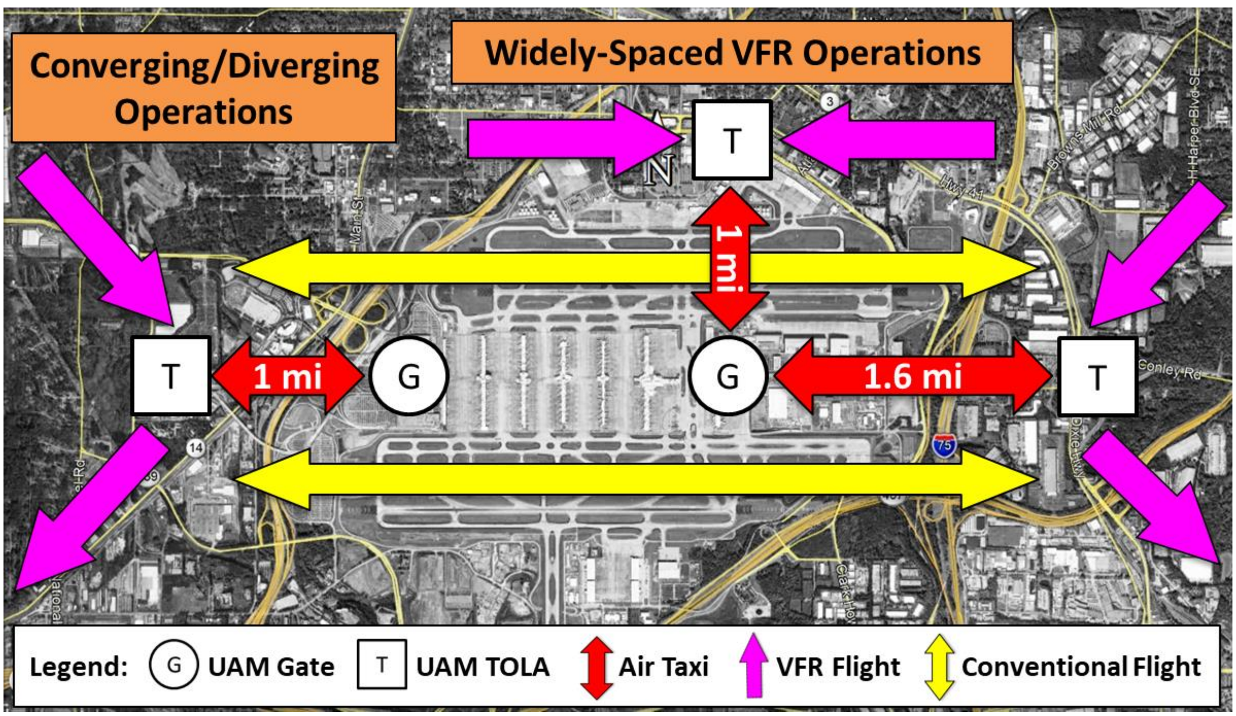


Fig. 70 Notional converging/diverging and widely-spaced operations for UAM integration at Atlanta International Airport in either east or west flow patterns. *Map © 2019 Google.*

PinS arrivals to the green region of Fig. 69 may support IFR UAM arrivals with reduced complexity compared to converging IFR arrivals. PinS operations north of the airport would require a 2.5 mile visual flight segment to the terminal. The visual segment could follow either I-75 or I-85 from the MAPt to the airport. (Note that UAM aircraft could not continue directly to the terminal under visual flight as wake vortex separation requirements would not be met between the runways; rather, air taxiing or ground transportation would be required.)

8.5.2 UAM Operations in Proximity to Boston International Airport

BOS provides a number of advantages over ATL in terms of UAM access to the airport terminals. First, the ends of inactive crossing runways have sufficient separation from the active runways to support converging arrivals (i.e., LAHSO) and diverging departures in any of the four BOS flow patterns. Furthermore, as displayed in Fig. 71, runway 15R (positioned directly north of the terminal) could support widely-spaced VFR arrivals in a southwest flow pattern. ATL did not have this opportunity due to its parallel runway configuration.

Second, the BOS terminal is not imbedded between parallel runways as was the case at ATL. Converging or diverging UAM operations could therefore potentially utilize a TOLA co-located with the terminal for some flow patterns (such as the southwest flow pattern displayed in Fig. 71).

Third, visual flight and air taxi segments from remote TOLA locations may provide more direct access to the terminal at BOS than at ATL. In the southwest flow pattern, widely-spaced VFR arrivals may be flown to a TOLA located on land or water a half mile northeast of the terminal. IFR PinS arrivals may be flown to a MAPt over water approximately 1.5 miles from the terminal. Either integration strategy would require an air taxi or visual flight segment to connect to the terminal (if weather conditions permit and air taxiing is authorized beyond airport boundaries). This last-mile flight segment may occur entirely over water up to the airport boundary as displayed for a PinS arrival in Fig. 72. Neither integration strategy would require UAM flight beneath conventional aircraft operations (including missed approaches) during a southwest flow pattern.

For the southeast and northwest flow patterns, widely-spaced VFR or PinS arrivals may be located approximately 1.5 miles from the terminal. However, the northeast flow pattern (used ~18% of the time) was more challenging for UAM integration and would require an air taxi or visual segment of approximately 2.3 miles to access the terminal from the northwest.

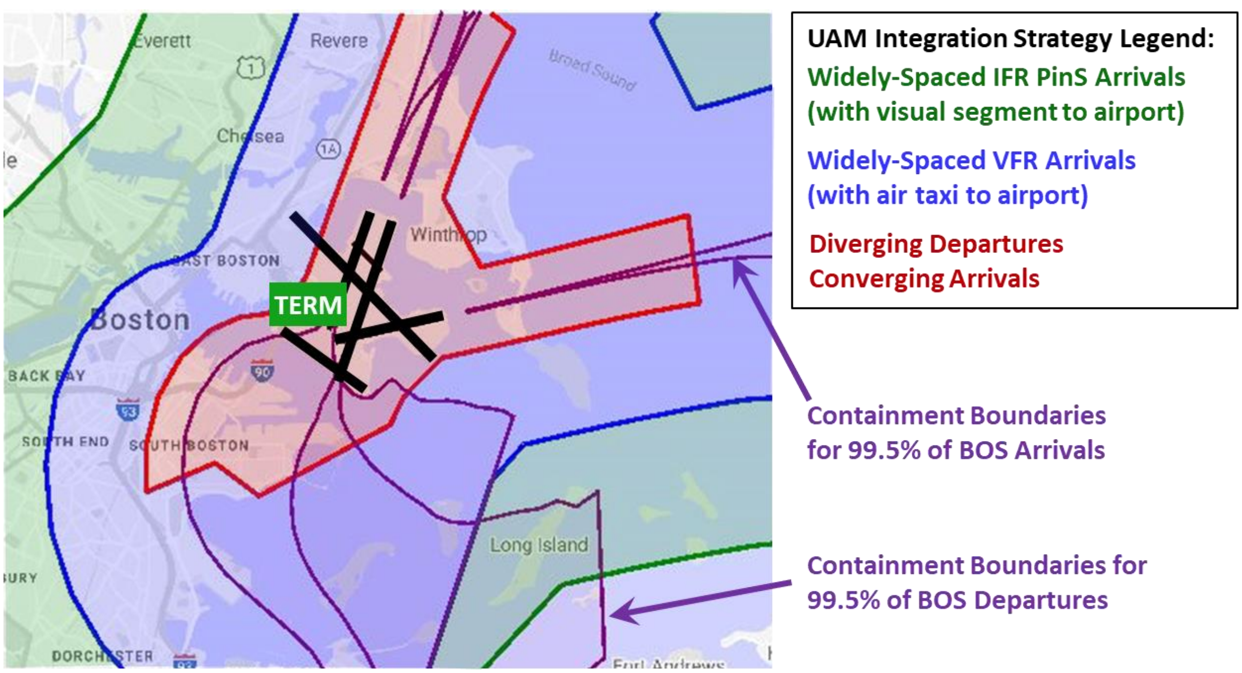


Fig. 71 Airport integration strategies at BOS in a southwest flow pattern (28% frequency).

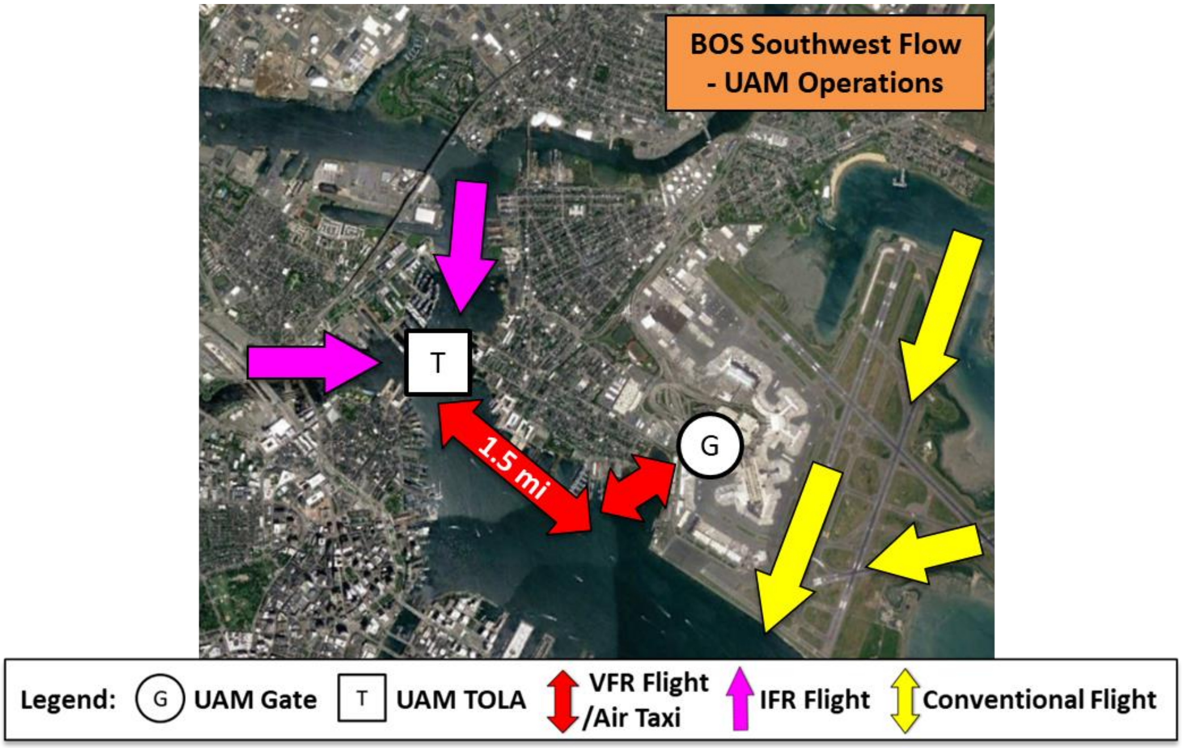


Fig. 72 Notional IFR PinS arrival procedure for BOS in a southwest flow pattern (28% frequency) or northwest flow pattern (37% frequency).

8.5.3 UAM Operations in Proximity to San Francisco International Airport

SFO operates in a west flow pattern 83% of the time. In the west flow pattern, aircraft exclusively arrive from the southeast and depart from crossing runways to the northeast. As a result, UAM aircraft may operate west or south of the airport without anticipated interactions with conventional flights. UAM may also operate northwest of the airport without interacting with standard arrivals or departures, but requiring underflight of missed approach operations.

The SFO terminal is also located to the west of the airport and is not imbedded between runways. Converging UAM arrivals may be capable of accessing TOLAs co-located with the terminal or its parking infrastructure directly. Widely-spaced VFR arrivals to the blue region of Fig. 73, may also support UAM access to TOLAs in close proximity to the terminal. An example layout of this procedure is shown in Fig. 74.

For IFR operations, a PinS to a TOLA due west of the airport followed by a visual segment would overfly a number of densely populated residential communities as notionally depicted in Fig. 74. To mask noise and reduce population overflight, a PinS could alternatively be developed northwest of the terminal to a MAPt located above the intersection of I-380 and Highway 101. The visual or air taxi segment could follow Highway 101 to reach the terminal.

IFR PinS arrivals from the northwest may have an additional challenge of interactions with conventional arrival missed approach paths. These interactions are an area of future research. Furthermore, when SFO operates in a different flow pattern than west flow, conventional aircraft departures operations may limit PinS or widely-spaced operations from the northwest.

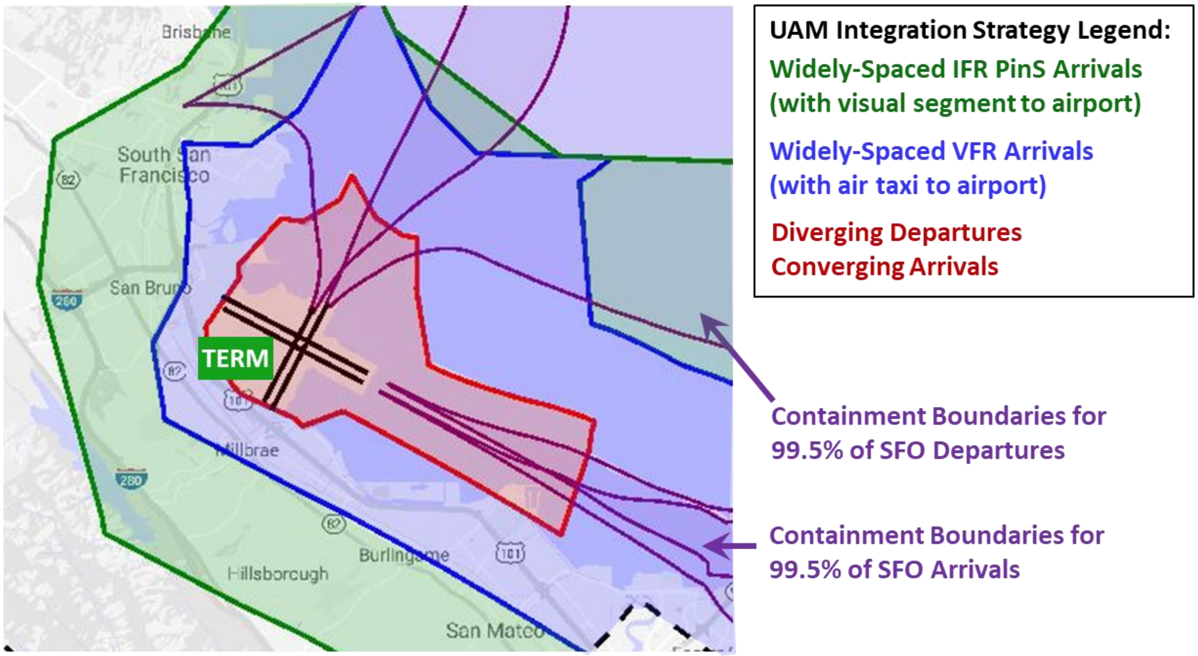


Fig. 73 Airport integration strategies at SFO for a west flow pattern (83% frequency).

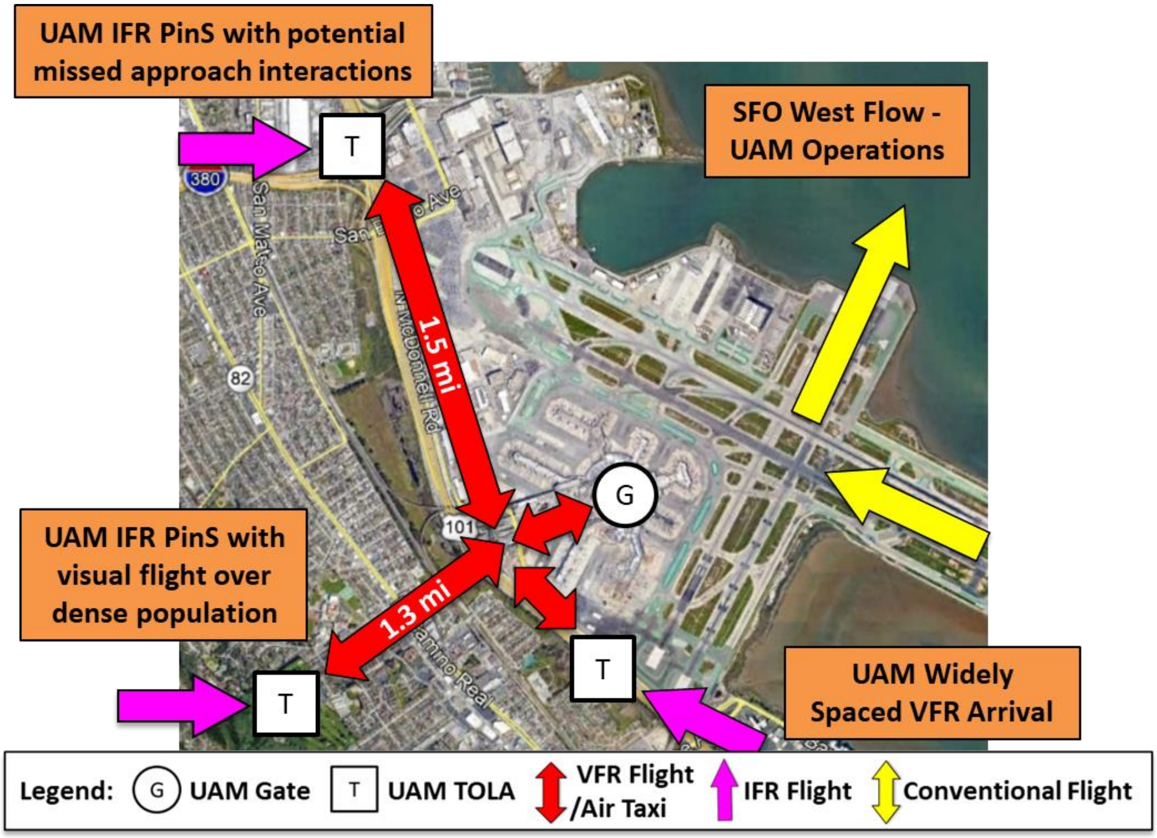


Fig. 74 Notional UAM arrival procedures for SFO in a west flow pattern (83% frequency).

8.6 Conclusion

This chapter evaluated procedures to enable simultaneous and non-interfering UAM operations at TOLAs that are in close proximity to airports. Due to the proximity of these TOLAs to conventional aircraft operations, procedurally segregated airspace cutouts could not be developed to support UAM access to them.

The findings of this chapter also support simultaneous IFR UAM operations at TLOF pads in close proximity to one another (e.g., at a multi-pad TOLA). The analyses in Chapter 5 indicated that TOLA throughput was restricted to approximily 50 arrivals or departures per hour for IFR operations on a single TLOF pad. Each independent TLOF pad added to a TOLA through the procedures considered in this chapter may therefore act as a multiplier of IFR throughput capacity.

Four promising strategies were identified to support UAM operations at airports including the connection of passengers to/from the commercial terminals. These strategies were:

1. converging arrivals,
2. diverging departures,
3. widely-spaced VFR arrivals with an air taxi segment, and
4. widely-spaced IFR arrivals on a Point in Space (PinS) procedure.

Each strategy utilizes either existing flight procedures or modifications of existing flight procedures based upon anticipated flight capabilities of UAM aircraft. Furthermore, the strategies were anticipated to minimize requirements for additional controller staffing and/or new CNS technologies.

The key conclusions of this chapter are:

1. UAM operations under visual flight rules (VFR) to TOLAs at or near airports are constrained by wake vortex separation requirements and controller workload. Converging arrivals and diverging departures mitigate the wake vortex restrictions. Land and Hold Short Operations (LAHSO) may enable the use of existing, cross-wind runways for independent VFR UAM operations. Alternatively, widely-spaced VFR arrivals followed by an air taxi segment may mitigate wake vortex interactions and minimize controller workload contributions from UAM.

2. UAM operations under instrument flight rules (IFR) to TOLAs at or near airports are most constrained by separation minima on final approach. Point in Space (PinS) approaches or Simultaneous Converging Instrument Approaches (SCIA) are promising strategies to enable IFR arrivals to TOLAs near airports. PinS approaches require weather conditions that permit visual flight following the missed approach point (MAPt). SCIA is limited for application to UAM by current design requirements, but potential low-speed flight performance of UAM aircraft may enable adjustment of these design requirements.

3. UAM aircraft classification as a helicopter (as opposed to a fixed-wing) provides numerous benefits for operations near airports. First, Part 135 operators (the likely operating category for UAM services) have a VFR flight visibility minimum of 0.5 NM when classified as a helicopter, but a 3.0 NM minimum when classified as a fixed-wing. Second, only helicopters

are authorized to air taxi or conduct PinS approaches. Finally, helicopters benefit from a number of separation minima reductions due to their unique performance capabilities.

4. Airports with terminals that are imbedded between runways reduce the opportunity for simultaneous and non-interfering UAM services to the terminal, especially in IMC.
5. The established on RNP (EoR) procedure is an enabling navigational capability that reduces controller workload and simplifies UAM IFR integration near airports.

8.7 Limitations and Future Work

Future work is recommended to investigate a number of policy and regulatory changes that are beneficial to the deployment of the concepts presented in this chapter. In particular, conducting a safety risk management evaluation of the following concepts is necessary before they could be deployed to support UAM integration at airports.

First, Simultaneous Converging Instrument Approaches (SCIA) currently require three miles of separation between the missed approach points of the two procedures. Future work may investigate if this separation may be reduced based upon the slower approach speeds and higher maneuverability that may be achieved by some UAM aircraft. Relief from this requirement by reducing the MAPt spacing will enable the application of SCIA for UAM in more scenarios and at more airports.

Second, air taxiing is currently restricted to occurring within the lateral boundary of the airport property. Most airports could not support air taxi connections to widely-spaced TOLAs without relief from this design restriction.

Finally, Land and Hold Short Operations (LAHSO) may support UAM operations on existing runways at airports. However, LAHSO is currently limited to VFR operations only. Future work may investigate how LASHO could be supported in instrument conditions.

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9 Analysis of UAM Scaling Potential in Major U.S. Cities Subject to Near-Term Air Traffic Control Constraints

Air traffic control may restrict the scale of UAM operations in airspace as well as at TOLAs due to separation requirements, controller workload limitations, and/or special use airspace.

This chapter presents an analysis of UAM mission coverage (i.e., the portion of a region's population that UAM aircraft could access without ATC interaction) in the largest 34 U.S. metropolitan areas. This analysis provides a first-order estimation of the severity of the ATC constraint for UAM operations in each area.

The 34 metropolitan areas represent potential near-term markets for UAM due to their population size, congestion, and sprawl. The areas are also characterized by significant variation in city topology, weather conditions, airport locations, and the volume of current aviation operations. These attributes were anticipated to influence the severity of the ATC constraint for UAM scaling.

The goal of this chapter is to compare UAM mission coverage between each city for various ATC integration scenarios (e.g., VFR airspace cutouts, access to SUA, etc.) in order to:

1. determine the effectiveness of airspace cutouts, access to SUA, and access to controlled airspace with low traffic volumes as strategies to reduce the severity of the ATC constraint,
2. characterize city to city variation in the impact of the ATC constraint on UAM scaling, and
3. rank the largest U.S. metropolitan areas by the difficulty of ATC integration for UAM flights and the mission coverage potential for UAM services.

9.1 Approach

The approach taken to assess UAM mission coverage is displayed in Fig. 75.

First, 34 metropolitan statistical areas (MSAs) with more than two million inhabitants were selected as potential early adopting locations for UAM. An MSA is one or more core urban areas and its adjacent communities that have a substantial population and a high degree of economic and social interaction with one another [147]. MSAs and their geographic boundaries are defined by the Office of Management and Budget and the Census Bureau and were perceived by the author as an appropriate geographic scale on which to consider the operation of a notional UAM system.

Second, terminal controlled airspace, SUA, and conventional flight operations were modeled in each MSA. The models defined the three-dimensional boundaries of each airspace construct. These three airspace "constructs" were anticipated to be the primary attributes of ATC that may limit UAM access to surface locations in an MSA.

Next, potential demand for two types of UAM services was estimated within each MSA. First, the population distribution of the MSA was assumed as a proxy for the demand for an air taxi service. Second, individuals who travel more than 60 minutes to and from work (each way) were assumed to represent potential demand for UAM commuter services. Willingness to pay was not estimated for either customer and demand type. This analysis therefore does not provide a market estimate for a specific UAM price-point, but rather evaluates what percentage of the estimated total addressable UAM market for these two service types may be impacted by ATC.

Fourth, mission coverage was estimated in each MSA by determining the portion of the population or long-duration commuters that reside beneath the airspace constructs; these areas may not be accessible to UAM. Five ATC ConOps "scenarios" were evaluated that represented different levels of UAM access to the airspace constructs. The scenarios assessed the effectiveness of various strategies to relieve the ATC constraint.

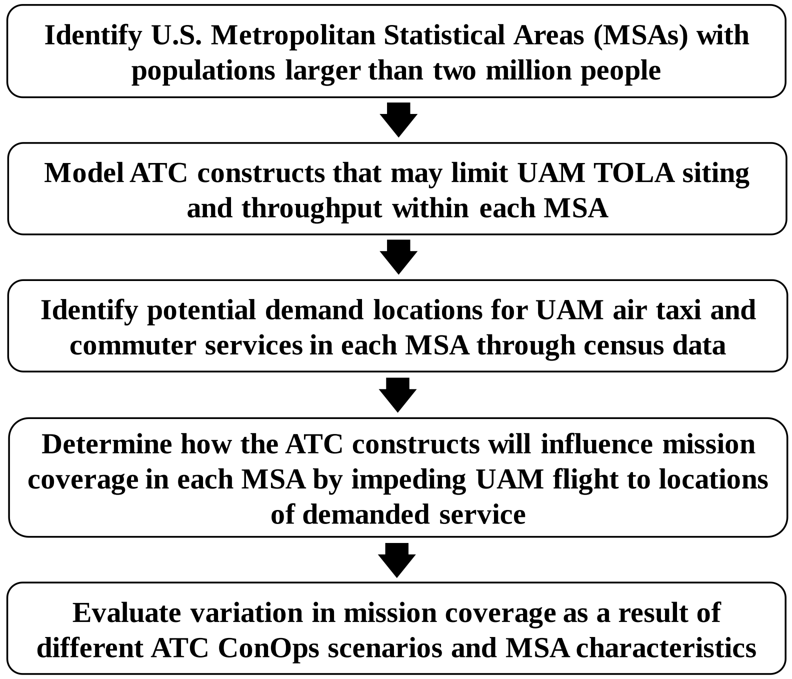


Fig. 75 ATC assessment approach.

Fig. 76 displays example results from the fourth step of the assessment approach. In this example, the boundary of the St. Louis MSA is indicated in magenta. The population density of the MSA is shown with a black to green to yellow to white heatmap. The long-duration commuter residences and workplaces are indicated with orange triangles and circles, respectively. The left sub-image displays unconstrained UAM mission coverage, and the right sub-image shows the impact of UAM exclusion from controlled airspace.

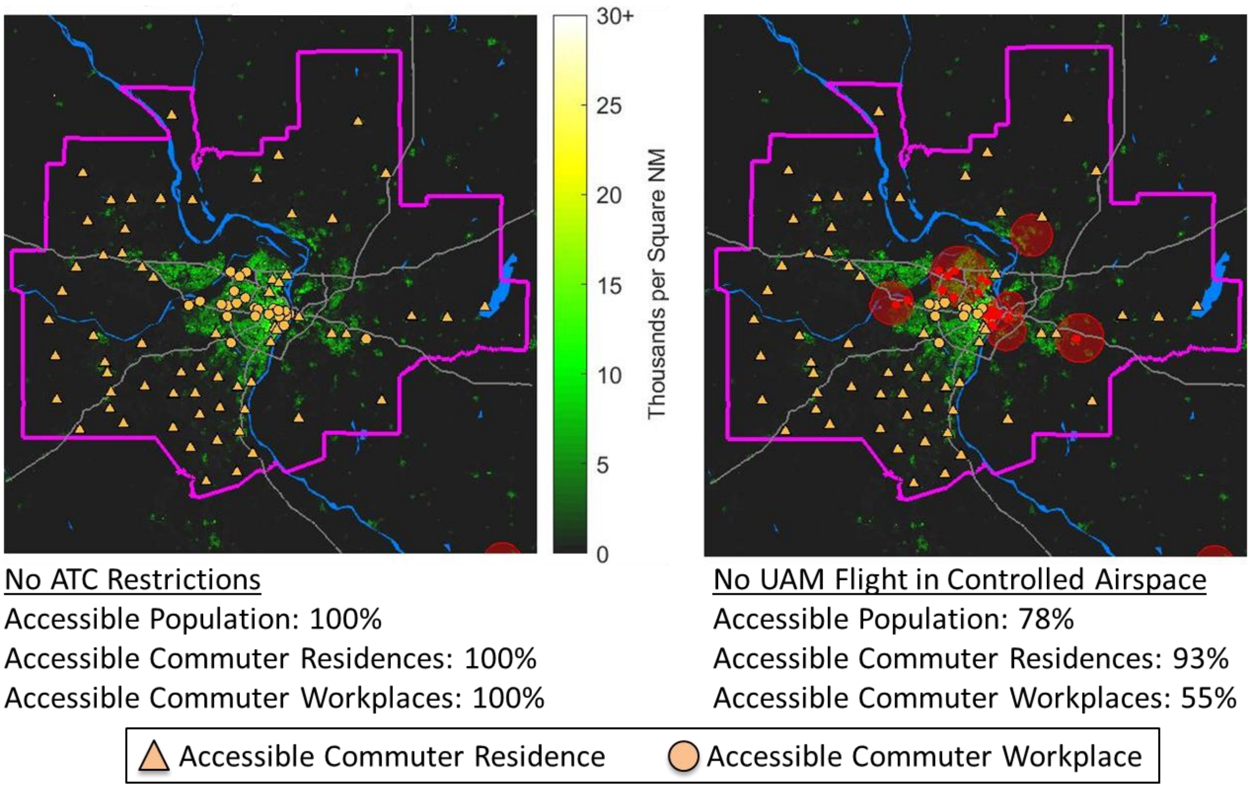


Fig. 76 Example UAM mission coverage in the St. Louis MSA.

The final step of the assessment reviewed the mission coverage results from the 34 MSAs to (1) identify variation in mission coverage between the areas, and (2) assess the effectiveness of different UAM integration strategies contained within the five ATC ConOps scenarios to relieve the ATC constraint. It should be noted that the mission coverage estimates for population and long-duration commuters were not intended as a market estimate for UAM (as there was no analysis of the customer's ability to afford the service). Rather, mission coverage was assumed as an estimate of the total addressable market from which UAM may serve a subset of the demand.

9.2 Metropolitan Area Selection

Initial markets for UAM services are anticipated to be located in metropolitan areas with large populations; these areas are generally assumed to have longer commute distances and/or durations as well as a larger number of potential customers for UAM. This analysis therefore considered all metropolitan statistical areas (MSAs) in the United States with a population of greater than two million as potential early adopter markets for UAM.

An MSA is a geographic region that has a densely populated core city(s) with close economic ties and worker mobility to and from the surrounding communities [147]. Consulting Census Bureau estimates for 2018 MSA populations, 34 MSAs were identified in the U.S. with populations of over two million. Fig. 77 displays each MSA.

As a note, due to the compact nature of New England, the Boston area was modeled with the Census Bureau's combined statistical area (CSA) rather than the MSA. The CSA included all of the Boston MSA, as well as multiple surrounding cities within approximately 60 miles of Boston.

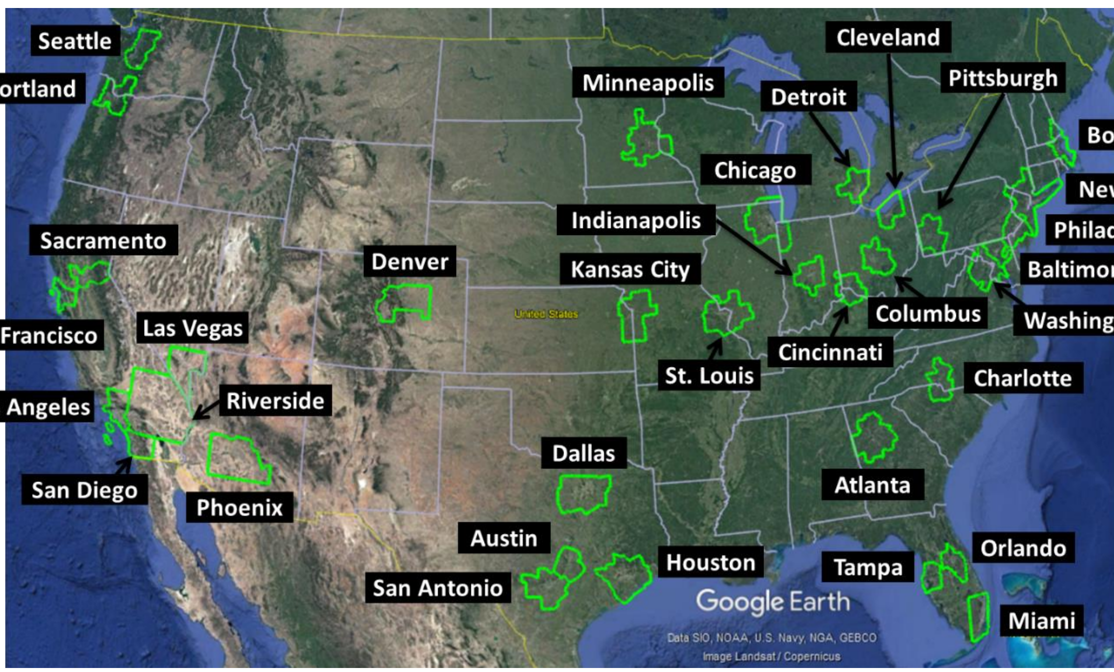


Fig. 77 Metropolitan statistical areas in the U.S. with over two million inhabitants.

9.3 Modeling of ATC Constructs in each MSA

The mission coverage analysis focused exclusively on three ATC constructs as the primary features or airspace that may limit UAM services in a city. The modeling approach taken for each of the three airspace constructs is described below:

Class B, C, and D Controlled Airspace

Entry into these terminal-area controlled volumes requires, at a minimum, that two-way communication is established with the tower controller. UAM operations could be excluded from these volumes if controller workload is high. Controlled airspace volumes were modeled based on the FAA 28 Day National Airspace System Resource, effective July 1, 2018.

It was anticipated that controller workload limitations and UAM access to controlled airspace would vary depending upon the current amount of air traffic and congestion in a controlled airspace. Therefore, for the purposes of this analysis, controlled airspace was distinguished by the traffic volume that its central airport supported.

Airports that supported at least 20,000 annual commercial operations, over 75,000 total annual operations, or permanent military operations were termed “high-traffic” airports for this analysis. Airports that did not support air traffic meeting any of these three criteria were termed “low-traffic” airports for this analysis. All class B and C airspace were associated only with high-traffic airports. class D airspace surrounded both high and low-traffic airports.

Special Use Airspace (SUA)

SUA protects aviation or surface activities of a unique nature. Various types of SUA exist in the U.S. national airspace as described in Section 6.5.1 and include:

- Prohibited airspace
- Restricted airspace
- Temporary flight restrictions (TFRs)
- Military operating areas, warning areas, and alert areas
- Special conservation areas

Of the SUA types, TFRs most commonly appeared within the MSAs. The majority of the TFRs were positioned around large, open-air stadiums, and were generally active for less than 50 hours per year. However, TFRs around baseball stadiums were active for as many as 400 hours per year. TFR volumes were modeled for this analysis based upon NOTAM FDC 7/4319.

The other types of SUA were less frequently present in the MSAs. Three dimensional models for each of the other types of SUA were developed based upon geometric data collected from FAA VFR Aeronautical Charts.

Heavily Used Airspace

It was assumed in this study that UAM operations must not interfere with high-volume conventional flight operations. Section 7.2 demonstrated through radar trajectory analysis that large, transport aircraft operate exclusively on airport approach and departure procedures. Therefore, the approach taken in this analysis was to model the airspace volumes used for approaches or departures at high-volume airports as airspace that is heavily used by conventional aircraft where UAM may be unable to fly.

To model arrival and departure operations at high-traffic airports, statistical containment boundaries for transport and regional aircraft flights were developed from radar tracking data through the approach introduced in and Chapter 7. Because radar data was not available at every airport evaluated in the MSAs (~140 airports), a simplified, representative containment boundary for arrivals and departures was developed as the average of the boundaries from three airports at which radar data was available, namely Boston, Atlanta, and San Francisco international airports. The containment boundaries for these airports were defined based on the airspace extent used by the 99.5th percentile aircraft operation.

The representative containment boundary was applied to every other high-traffic airport by assuming straight-in arrivals and straight-out departures. When runway utilization data was available at these airports, containment boundaries were only generated for runways with utilizations (by time active annually) of greater than 5%.

VFR separation minima were then applied to the containment boundaries in the same manner as introduced in Chapter 7. VFR separation requirements were 1.5 NM laterally and 500 ft vertically. Airspace that resided beyond the separation minima was considered to be procedurally segregated from airspace that was heavily used by conventional flight operations (i.e., airspace that may potentially support a VFR cutout as introduced in Chapter 7). IFR separation requirements and IFR cutouts were not considered in this initial analysis. Future work should investigate the benefit of static and dynamic IFR cutouts as a means to relieve IFR ATC constraints for UAM scaling.

Fig. 78 displays the representative 99.5th percentile containment boundaries for arrival and departure operations developed for San Diego International Airport in its primary runway flow pattern (i.e., west flow). Note that a separation minima offset was not applied to the containment boundaries in Fig. 78. The representative departure containment boundary displays a higher degree of dispersion than that of the arrivals. However, the arrival containment boundary has a lower containment floor altitude than the departures.

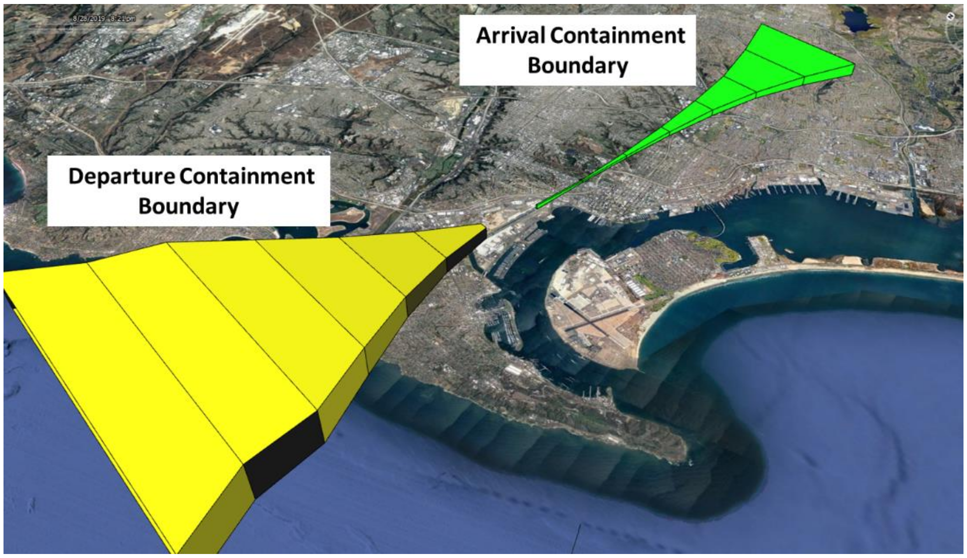
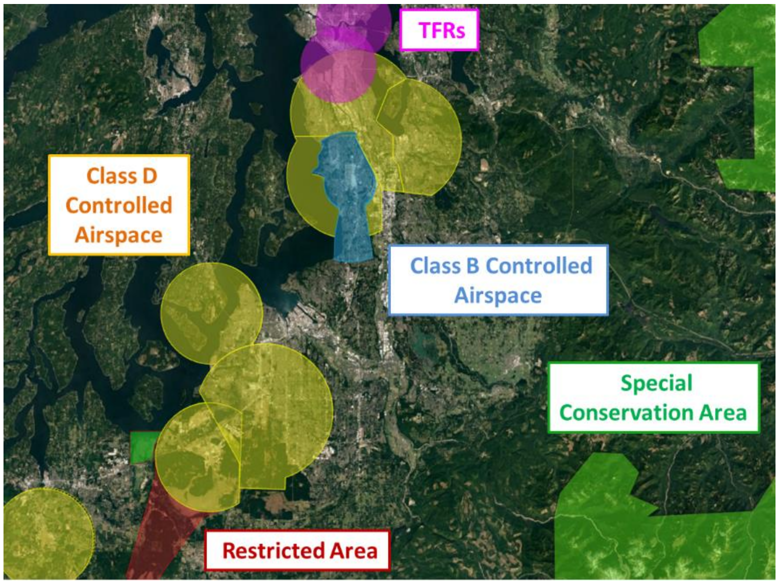
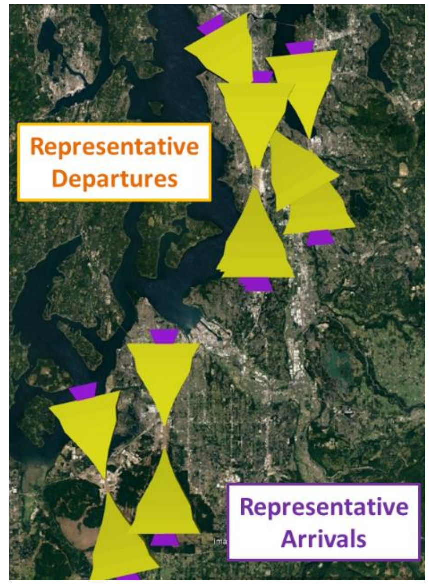


Fig. 78 Representative 99.5th percentile containment boundaries for San Diego International Airport in west flow configuration.

Controlled airspace, SUA, and heavily used airspace were modeled in each MSA through the methods and resources introduced above. As an example, the left subfigure of Fig. 79 displays the controlled airspace and SUA in the Seattle-Tacoma region. The simplified arrival and departure containment boundaries for the high-traffic airports are presented in the right sub-figure.



Controlled Airspace and SUA



Arrival/Departure Operations

Fig. 79 ATC constructs modeled in the Seattle-Tacoma area.

9.4 UAM Potential Demand in each MSA

ATC primarily affects UAM scalability by influencing the number of aircraft (if any) that may serve TOLAs in specific surface locations. However, access to TOLAs in all areas is not necessarily of equal value in terms of UAM demand and mission coverage. For example, if ATC restricts UAM access to rural or sparsely populated areas where there is low demand, then the severity of the impact is minimal in terms of UAM mission coverage. Alternatively, if ATC limits UAM access to commuter neighborhoods or city centers, the impact of ATC on mission coverage may be profound.

Considering this, UAM demand was spatially modeled in each MSA through three different approaches:

1. Population density was assumed as a proxy of demand for the air taxi mission.
2. Census tracts into which long-duration commuters travel were assumed to be potential workplace locations for a commuting mission.
3. Census tracts from which long-duration commuters travel were assumed to be potential residential locations for a commuting mission.

Further detail on how each of these demand types were modeled is provided in the following sections:

9.4.1 Air Taxi Demand Modeling

The air taxi mission concerns point to point travel between locations of interest. Potential locations of interest include sporting events, airports, commercial areas, recreational areas, and tourist sites, among others. This analysis assumed that air taxi demand was proportional to population density. The assumption was based on an expectation that potential customers are likely to start or end their air taxi mission near their place of residence. Additionally, many of the "special attractor" points of interest such as hospitals and sports arenas are distributed proportionally with population density.

To model population density, census block data for the United States were obtained from the U.S. Census Bureau. The data was re-gridded onto a 0.1 NM by 0.1 NM grid that spanned the entire MSA. The population was assumed to be distributed evenly within each census block during the re-gridding process. The product was a regular grid of population data on which mission coverage could be evaluated.

9.4.2 Commuter Demand Modeling

The UAM commuter mission concerns travel between residential areas and workplace locations. The primary benefit of UAM over existing transportation modes is reduced door to door travel time through higher travel speeds and overflight of obstructions or congestion. Therefore, potential demand for the UAM commuter mission was assumed to be correlated with the duration of the commute a customer currently experiences.

The Census Transportation Planning Product[13] (CTPP) was used to identify potential commuter demand for this type of UAM mission. The CTPP bases commuter estimates on data from the 2012-2016 5-year American Community Survey (ACS).

9.4.2.1 Current Long-Duration Commuter Demand

This analysis assumed that commuters who travel more than 60 minutes to and from work each day (>120 minutes total daily commuting) represent potential demand for UAM. These long-duration commuters may be more likely to substitute their current transport modality with UAM flights (i.e., substitutional demand) than individuals with shorter duration commutes.

The CTPP was queried to identify census tracts in the MSA from which more than 500 commuters travel 60 minutes or more to work. These census tracts were assumed to be potential demand origin locations for the commuter UAM mission. A minimum threshold of 500 long-duration commuters per census tract was implemented to represent that UAM services will target concentrations of demand to justify investments in TOLA infrastructure.

The CTPP was also queried to identify census places into which more than 500 commuters travel 60 minutes of more for work. These census places were assumed to be potential demand sink locations for the commuter UAM mission.

It should be noted that the residential analysis was conducted with census *tracts* as the base unit while the workplace analysis was conducted with census *places* (a larger geographic area) as the

[13] https://www.fhwa.dot.gov/planning/census_issues/ctpp/

base unit. This difference was the result of data availability in the CTPP. Commuter flows to workplaces were not reported in the CTPP at the census tract level. The limitation of using census places was that the locations of workplaces were not as spatially resolved.

To address this limitation, it was assumed that long-duration commuter workplaces were distributed within a census place similarly to all other commuter workplaces. The total number of inbound commuters was reported at the census tract resolution in the CTPP. Therefore, the CTPP was leveraged to identify the distribution of commuter workplace locations among the census tracts within each census place. The long-duration commuters for that census place were then allocated to each census tract according to this distribution.

Finally, it should also be noted that the commuters traveling from each residential area are not necessarily traveling to the same workplace. Rather than identifying specific commuter flows between two locations, the CTPP was used to identify source locations from which commuters flow to any workplace locations. Workplace locations were determined in the same manner.

9.4.2.2 Induced Long-Duration Commuter Demand

A potential ramification of the introduction of UAM is that the service may *induce* new demand by providing greater convenience of travel compared to current transportation modes [42]. For example, an individual may currently choose not to live in a community that is 90 minutes away from work by car or train. However, this same individual may reconsider that decision if the same community is only 20 minutes away when using a UAM service.

As an estimate of induced demand, this study identified residential areas that currently support between 250 and 499 individuals who travel more than 60 minutes to get to work. While these communities are below the 500-person threshold chosen to represent promising demand sources for UAM, it is possible that the introduction of UAM may induce increased demand in these communities.

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9.4.3 Example UAM Demand Patterns

Potential air taxi and commuter demand was identified in the 34 MSAs. The distribution of demand in a given MSA displayed a number of differences based on regional topography and city size. These differences may impact UAM operations. Three representative examples are shared below.

First, Fig. 80 displays commuter demand for the Minneapolis MSA. Long-duration commuters nearly exclusively reside in census tracts located circumferentially around the city center at a distance of 15 miles or more. Conversely, workplaces to which commuter travel more than 60 minutes are concentrated within 15 miles of the city center.

This commuter demand pattern suggests that UAM services will primarily provide time benefits by covering distance more quickly (as opposed to providing time benefits by overflying surface obstruction or congestion). Furthermore, as is borne out in the analysis results, the distribution of residences around the city makes it less likely that a large proportion of them will be simultaneously inaccessible due to a given ATC construct. On the other hand, the concentration of workplaces in the city center increases the probability that a large percent of them may be blocked by an airspace construct (e.g., a SUA or controlled airspace).

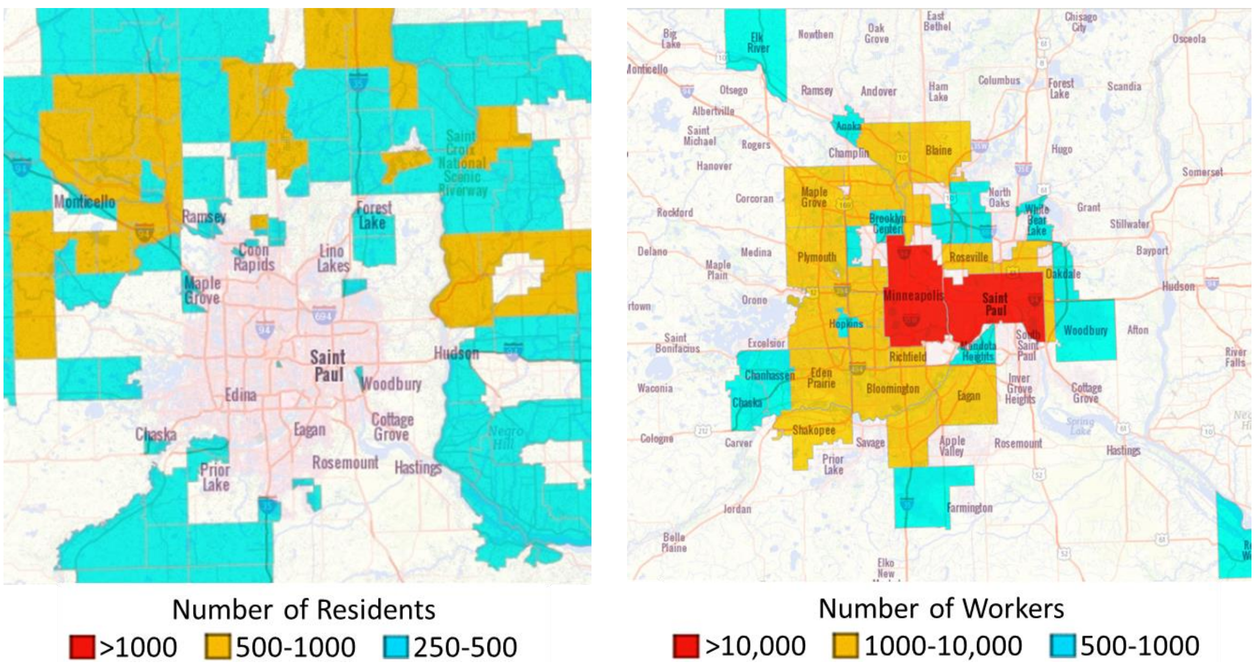


Fig. 80 Individuals commuting more than 60 minutes from their residence census tracts (left) to their workplace census places (right) in Minneapolis.

Fig. 81 displays the commuter demand for a portion of the Boston CSA. In comparison to Minneapolis, Boston is polycentric (i.e., dispersed) in its workplace locations, has long-duration commuter communities located within five miles of the city center, and has a larger number of communities with greater than 250 individuals who conduct long-duration commutes.

These differences in potential commuter demand are the result of Boston's larger population, more severe surface congestion, and extensive water barriers to surface travel. Considering these attributes, UAM services may potentially provide short-distance hops over congestion and water features in addition to longer distance trips in the Boston CSA.

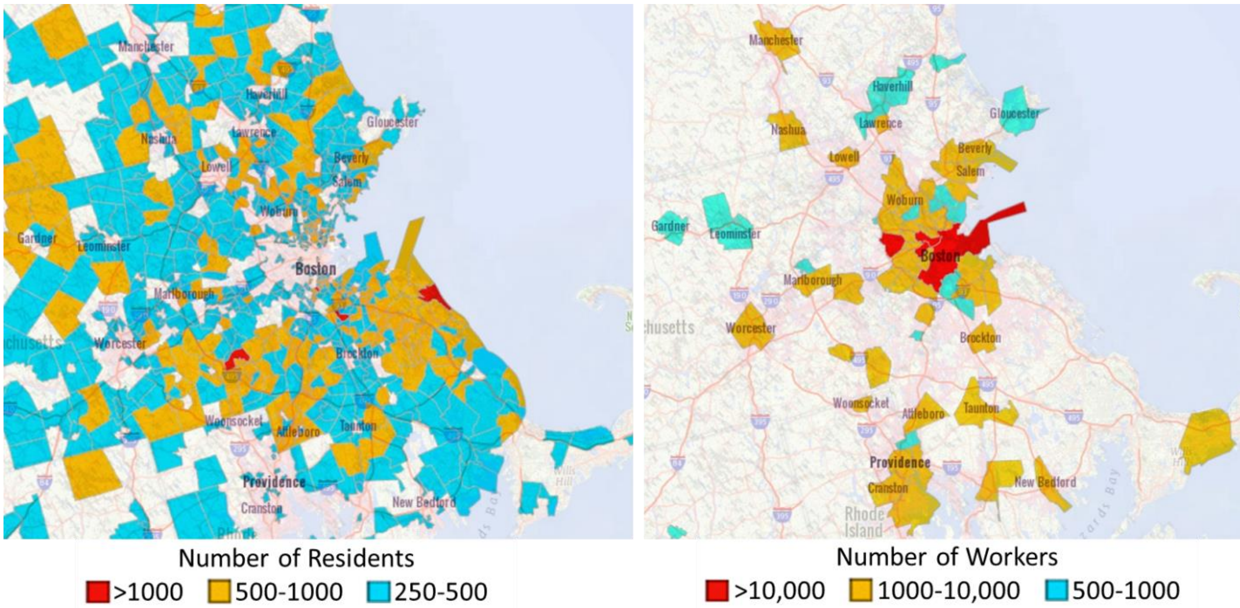


Fig. 81 Individuals commuting more than 60 minutes from their residence (left) to their workplace (right) in Boston.

Finally, Fig. 82 displays the distribution of population in the Miami and Columbus MSAs. The interesting difference between the two MSAs is the compact, circular layout of the Columbus population with a number of outlying settlements compared to the continuous strip of population along the coast in Miami with few outlying settlements.

This difference in population layout may make cities like Columbus more susceptible to ATC restrictions as a single SUA or controlled airspace could cover much of the densely populated city center.

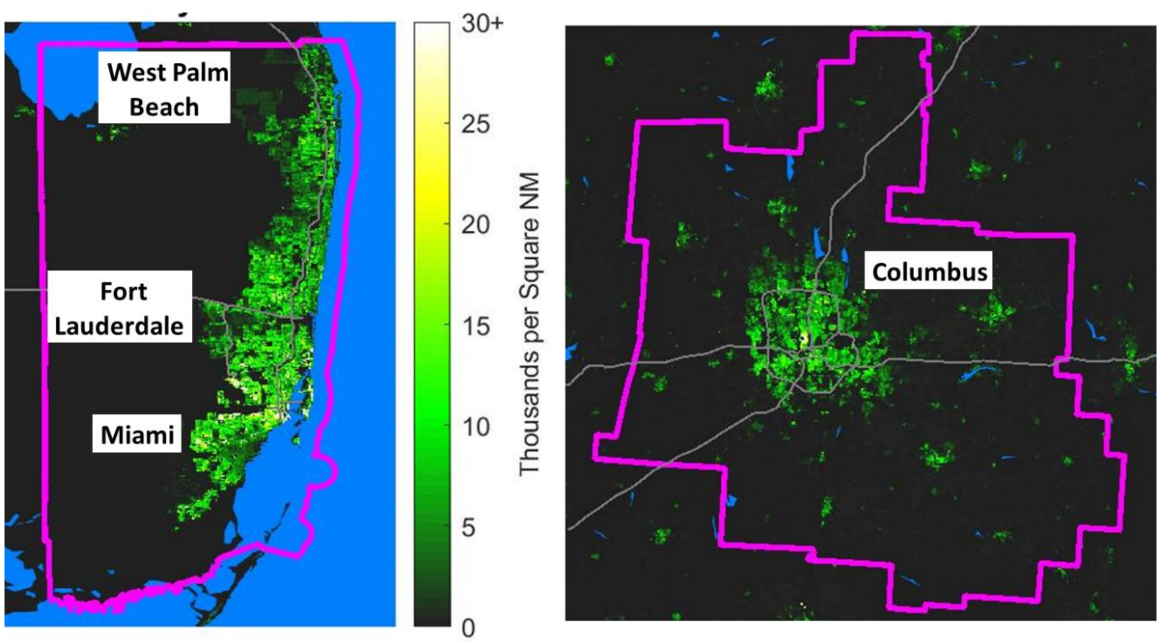


Fig. 82 Population density maps of the Miami and Columbus MSAs.

9.5 UAM ATC ConOps Scenarios

An objective of this chapter was to determine the effectiveness of VFR airspace cutouts, access to SUA, and access to controlled airspace at low-traffic airports as three strategies to reduce the impact of the ATC constraint on UAM scaling.

UAM mission coverage was therefore evaluated for five ATC ConOps scenarios that represented various implementations of these three strategies. Comparison between the scenarios reveals the sensitivity of mission coverage to each strategy and informs their potential effectiveness to relieve the ATC constraint. Table 22 summarizes the scenarios.

Table 22 UAM ATC ConOps scenarios for the MSA Analysis.

UAM ATC Scenario		Description
1	Fully segregated from SUA and terminal airspace	UAM flight is excluded from all SUA and terminal-area controlled airspace (i.e., class B, C or D airspace). This scenario is the current-day baseline condition for mission coverage as UAM vehicles could currently operate in this manner under VFR without any ATC interaction (i.e., unconstrained by ATC).
2	Access to SUA	UAM flight is excluded from any controlled airspace, but UAM aircraft may enter any type of SUA.
3	Access to controlled airspace at low-traffic airports	UAM flight is excluded from controlled airspace at high-traffic airports and any type of SUA. UAM aircraft may enter controlled airspace at low-traffic airports.
4	Access to static VFR cutouts	UAM flights may enter controlled airspace at high-traffic airports through the use of procedurally segregated VFR cutouts. UAM aircraft may not enter SUA or airspace at low-traffic airports.
5	Scenarios 2-4 combined	UAM may access SUA, controlled airspace at low-traffic airports, and static VFR cutouts.

9.6 MSA Analysis Results

The evaluation of UAM mission coverage in the 34 MSAs provides insight into the severity of the ATC constraint, the variation of the constraint between the different MSAs, and the sensitivity of the constraint to the six ATC ConOps scenarios. Population accessibility was considered to be a proxy of potential demand for an air taxi mission. Long-duration commuter residence and workplace accessibility were considered as estimates of potential demand for a commuter mission.

UAM mission coverage was calculated for each type of demand under each ATC scenario in every MSA. UAM aircraft were considered to be unconstrained by ATC to conduct missions to a given geographic area if the aircraft could fly at a minimum of 300 ft AGL without entering one of the active ATC constructs for the given ATC ConOps scenario.

The first three sub-sections below review variation in mission coverage as a function of differences between the MSAs and the ATC scenarios. Mission coverage is presented as a percentage of total potential demand in an MSA. Although a percentage metric does not provide direct information on the number of UAM flights (i.e., the scale of UAM operations), it enables a direct comparison of the effects of ATC between the different MSAs. The fourth section reviews the mission coverage in terms of total number of individuals that could potentially be reached by UAM flights.

9.6.1 Sensitivity of UAM Mission Coverage to Differences Between the MSAs

Table 23 summarizes the population accessibility, long-duration workplace accessibility, and two types of commuter accessibility for each MSA when UAM is excluded from all controlled airspace and SUA (i.e., fully segregated operations). The data from Table 23 support the following discussion of how mission coverage varies between the MSAs. Entries of "N/A" indicate cases where no census tracts within the MSA supported at least 500 long-duration commuters.

Table 23. Mission coverage when UAM is excluded from SUA and controlled airspace.

	Mission Coverage for Each UAM Service Type			
Metropolitan Area	*Total Population*	*Long-Duration Commuter Workplaces*	*Long-Duration Commuter Residences*	*Induced Commuter Residences*
Indianapolis, IN	85%	81%	93%	95%
Charlotte, NC	81%	30%	N/A	97%
Sacramento, CA	79%	54%	100%	94%
Pittsburgh, PA	77%	10%	100%	85%
Austin, TX	77%	38%	89%	88%
Cincinnati, OH	76%	46%	100%	93%
Kansas City, MO	76%	38%	100%	100%
Tampa, FL	75%	37%	85%	89%
St. Louis, MO	75%	35%	100%	91%
Detroit, MI	74%	64%	99%	82%
Atlanta, GA	72%	37%	83%	81%
Cleveland, OH	70%	25%	N/A	100%
Portland, OR	70%	68%	89%	75%
Philadelphia, PA	67%	60%	58%	66%
Orlando, FL	67%	33%	89%	67%
Chicago, IL	66%	24%	82%	68%
Riverside, CA	66%	35%	71%	65%
Denver, CO	64%	22%	73%	72%
Baltimore, MD	64%	38%	82%	74%
Houston, TX	62%	48%	71%	64%
Boston, MA	61%	15%	71%	62%
Columbus, OH	60%	15%	100%	91%
Minneapolis, MN	59%	21%	100%	92%
Phoenix, AZ	59%	26%	85%	66%
Seattle, WA	58%	35%	76%	69%
Dallas, TX	56%	19%	77%	75%
New York City, NY	55%	40%	49%	55%
San Antonio, TX	54%	65%	100%	74%
San Diego, CA	53%	30%	88%	61%
San Francisco, CA	48%	24%	71%	46%
Los Angeles, CA	44%	31%	54%	44%
Miami, FL	43%	18%	36%	47%
Washington, DC	34%	6%	58%	37%
Las Vegas, NV	24%	0%	N/A	21%

There is a large variation in mission coverage between the MSAs in Table 23. The first column indicates that if UAM aircraft do not interact with ATC (i.e., avoid controlled airspace and SUA altogether) then as little as 24% of an MSA's population (in Las Vegas) or as high as 85% of the population (in Indianapolis) may be accessible. This large difference indicates that the unique features of Las Vegas result in ATC scaling restrictions that are five times more severe than the restrictions in Indianapolis.

Fig. 83 displays how the various types of SUA and controlled airspace influence mission coverage in Indianapolis and Las Vegas. The population in the Indianapolis MSA is sprawling and only impacted by a single controlled airspace and SUA. Furthermore, the Indianapolis airport is located seven miles from the downtown area in a largely industrial region with little population; the influence of its controlled airspace on population access is therefore minimized.

In comparison, the entirety of the population of Las Vegas is concentrated near the downtown area. A large class B airspace as well as two class D airspace volumes overlay the majority of Las Vegas and are responsible for the highly restricted mission coverage. Las Vegas, similar to many western cities, also has a number of large ATC restrictions due to SUA on its periphery (primarily for military and special conservation purposes). However, these SUA have little influence on mission coverage as they are on the periphery of the city in areas with low population.

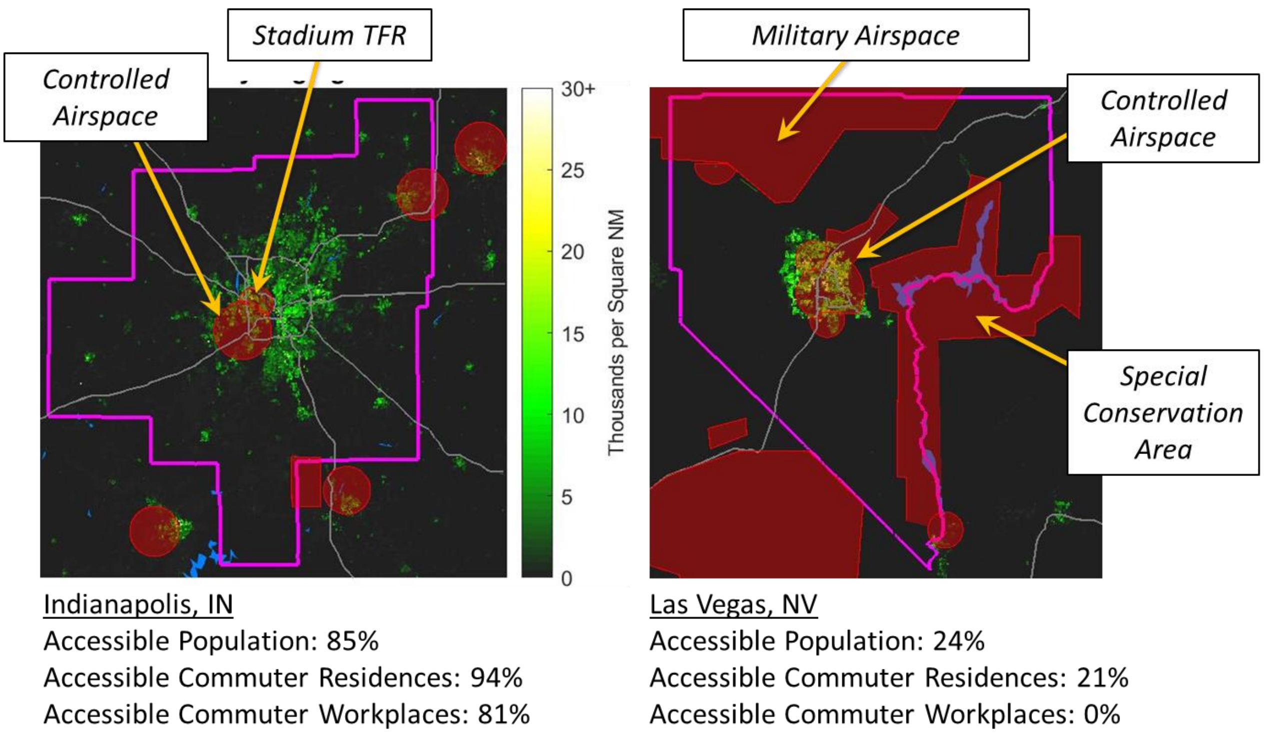


Fig. 83 Comparison of MSAs with population access least and most impacted by ATC when UAM is fully segregated (i.e., excluded from all SUA and controlled airspace).

Moving beyond these two extreme cases, the distribution of population accessibility for all 34 MSAs when excluded from controlled airspace and SUA is displayed in in Fig. 84. The top eight cities in Table 23 represent the first quartile of Fig. 84 and have an average population accessibility of 78%. In comparison, the eight cities in the bottom quartile have an average population accessibility of 44%. The median population accessibility is 65%.

The range of the upper quartile is less than that of the lower quartile in Fig. 84. This indicates that a few cities have uniquely severe restrictions due to ATC. For example, the left image in Fig. 85 displays how an SUA in Washington, D.C. potentially precludes UAM access to half of the population of the MSA and over 80% of the workplace locations to which long-distance commuters travel. Controlled airspace in the D.C. MSA also impacts UAM mission coverage to a similar degree as demonstrated in the right image of Fig. 85.

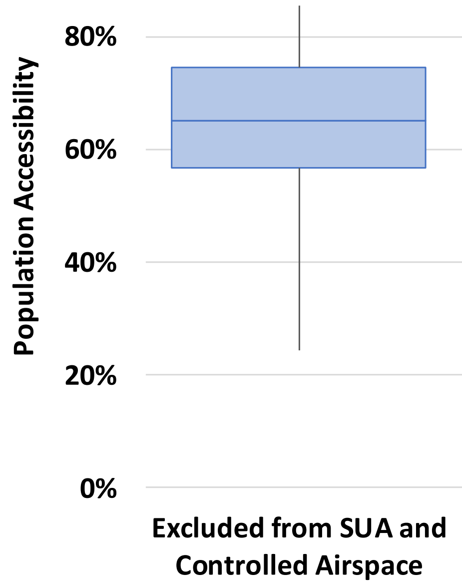


Fig. 84 Population accessibility for the 34 MSAs when UAM avoids all SUA and controlled airspace.

UAM coverage of long-duration and induced commuter demand is greater than the general population for most cities as displayed in the third and fourth columns of Table 23. On the other hand, workplace coverage is generally much less. This effect is pronounced in Fig. 85 where SUA or controlled airspace hinder UAM access to the densely populated, downtown region of Washington, D.C. where the vast majority of long-duration commuters travel to. The long-duration commuter residences, however, are geographically distributed on the periphery of the city center beyond the SUA. As a result, UAM is less constrained by ATC to provide services to these residential areas. Section 9.6.3 discusses this trend in greater detail.

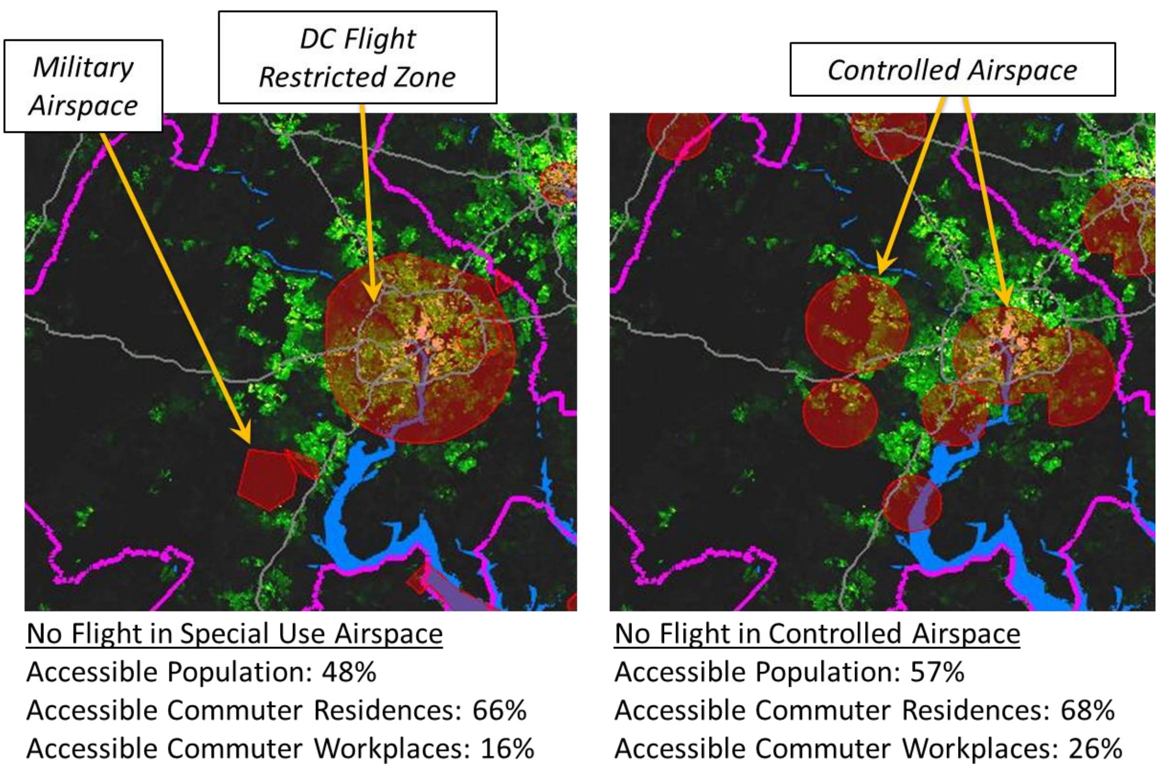


Fig. 85 SUA for security in Washington, D.C. precludes access to a majority of potential UAM mission demand. Controlled airspace also substantially restricts mission coverage.

The identification of attributes of an MSA that correlate with an increased severity of the ATC constraint may predict ATC impacts in cities beyond those evaluated in this study. Fig. 86 and Fig. 87 display the potential flight restrictions from controlled airspace and SUA for MSAs in the top and bottom quartiles of population accessibility, respectively.

Fig. 86 MSAs with low population access restriction in a fully segregated ATC scenario.

The following attributes were found to differ between the MSAs in the upper quartile and lower quartile of population accessibility:

- Number, location, and orientation of airports: MSAs in the upper quartile of mission coverage had one major airport located on the periphery of the city with flight paths that do not overfly the city centers. Cities more restricted by controlled airspace tended to have one or more high-traffic airports located near densely populated regions. These airports may also use runway configurations that directed arrivals or departures over densely populated areas.
- Prevalence of GA or military airports: MSAs with lower mission coverage tended to have multiple GA or military airports. These airports were frequently located within more densely populated areas.
- Coastal location: five of the eight cities in the lower quartile were coastal cities while only one of the eight cities in the upper quartile was on a coast. Coastal cities frequently had

high population densities near the shore and also one or more airports located near the shore; this co-location exacerbated the impact of the ATC constraint on mission coverage.

- City Population: the MSAs in the upper quartile of population access had a median population of 5.5 million compared 2.3 million in the lower quartile. City size may influence population accessibility as larger cities have expanded around airports that were initially on their periphery. It should be noted that although the percentage of the population that is inaccessible in the larger cities is higher, the total population that is accessible (i.e., the potential demand for UAM) generally remains higher as discussed in Section 9.6.4.

Except for in Washington D.C., SUA were found to impact population accessibility to a lesser degree than controlled airspace. The cities most impacted by SUA were generally coastal cities where baseball or football stadiums were located near densely populated areas.

While these trends may anticipate the severity of the ATC constraint in a city, the actual influence of ATC on UAM operations requires the evaluation of a city's unique characteristics.

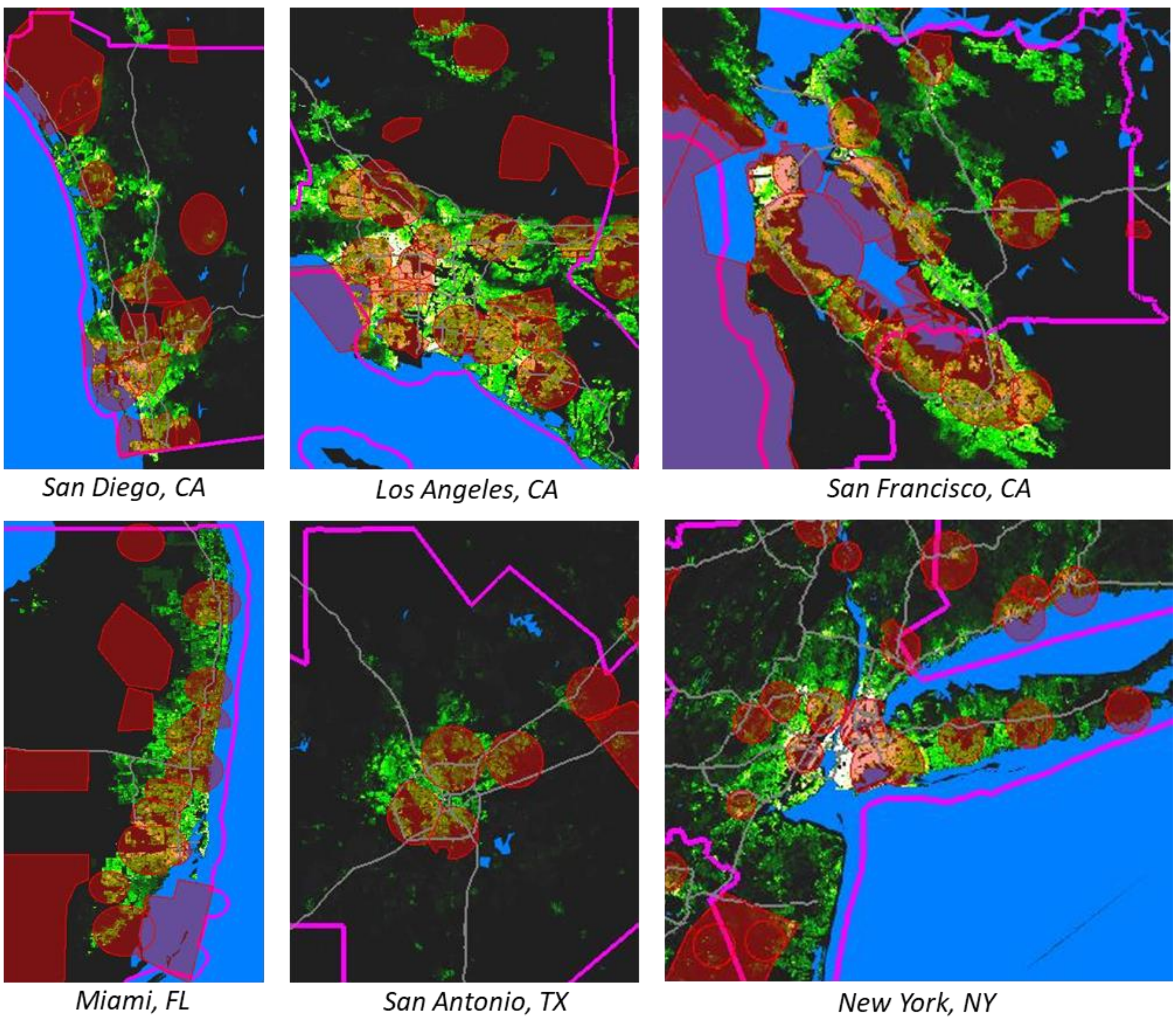


Fig. 87 MSAs with high population access restriction in a fully segregated ATC scenario.

9.6.2 Sensitivity of UAM Mission Coverage to ATC ConOps

Table 24 summarizes the population accessibility for each MSA under the five ATC scenarios; similar tables for workplace and commuter accessibility may be found in Appendix D. The variation in population accessibility between the scenarios indicates the potential effectiveness of access to SUA, access to low-traffic airport airspace, and the development of VFR airspace cutouts as strategies to reduce the impact of the ATC constraint.

Table 24. Percentage of the MSA population accessible in five ATC ConOps scenarios.

	Population Coverage by ATC ConOps Scenario:				
Metropolitan Area	*Fully segregated from SUA and terminal airspace*	*Access to SUA*	*Access to airspace at low-traffic airports*	*Access to static VFR cutouts*	*Access to SUA, low-traffic airspace, & static VFR cutout*
Indianapolis, IN	85%	89%	88%	87%	97%
Charlotte, NC	81%	84%	83%	88%	98%
Sacramento, CA	79%	79%	79%	89%	89%
Pittsburgh, PA	77%	85%	87%	80%	99%
Austin, TX	77%	85%	81%	84%	96%
Cincinnati, OH	76%	84%	76%	83%	93%
Kansas City, MO	76%	80%	84%	83%	97%
Tampa, FL	75%	75%	75%	87%	88%
St. Louis, MO	75%	78%	76%	87%	93%
Detroit, MI	74%	75%	82%	85%	96%
Atlanta, GA	72%	77%	77%	84%	94%
Cleveland, OH	70%	71%	83%	77%	95%
Portland, OR	70%	70%	70%	87%	88%
Philadelphia, PA	67%	70%	81%	79%	97%
Orlando, FL	67%	74%	69%	72%	85%
Chicago, IL	66%	77%	70%	77%	92%
Riverside, CA	66%	69%	66%	84%	87%
Denver, CO	64%	76%	64%	82%	93%
Baltimore, MD	64%	75%	64%	80%	94%
Houston, TX	62%	65%	70%	80%	94%
Boston, MA	61%	63%	74%	72%	93%
Columbus, OH	60%	66%	67%	75%	91%
Minneapolis, MN	59%	65%	59%	69%	94%
Phoenix, AZ	59%	62%	59%	80%	88%
Seattle, WA	58%	66%	61%	75%	87%
Dallas, TX	56%	60%	64%	73%	90%
New York City, NY	55%	57%	56%	76%	87%
San Antonio, TX	54%	56%	56%	80%	83%
San Diego, CA	53%	54%	53%	69%	77%
San Francisco, CA	48%	64%	48%	65%	86%
Los Angeles, CA	44%	54%	44%	67%	79%
Miami, FL	43%	44%	43%	67%	73%
Washington, DC	34%	57%	34%	44%	90%
Las Vegas, NV	24%	24%	25%	71%	76%

Fig. 88 presents a box plot of the data from Table 24 to display how the percent of the population that is accessible to UAM in the MSAs varies in response to the five ATC integration scenarios.

The first bar of Fig. 88 is identical to the data presented in Fig. 84 and indicates that the median population coverage for fully segregated UAM operations in the MSAs is 65%. This suggests that VFR UAM services could currently access 65% of the population in a typical MSA without ATC interaction or any ATC restrictions. UAM services to the remaining 35% of the population must enter SUA or controlled airspace and may be limited in scale by ATC.

The second bar displays population coverage if UAM were authorized to fly in SUA. Enabling UAM access to SUA increases the median population accessibility by 5% compared to the fully segregated scenario. However, exclusion from controlled airspace continues to impede scale-free UAM operations to 30% the median MSA's population. Access to SUA has a large impact on workplace and commuter residence coverage as discussed in section 9.6.3.

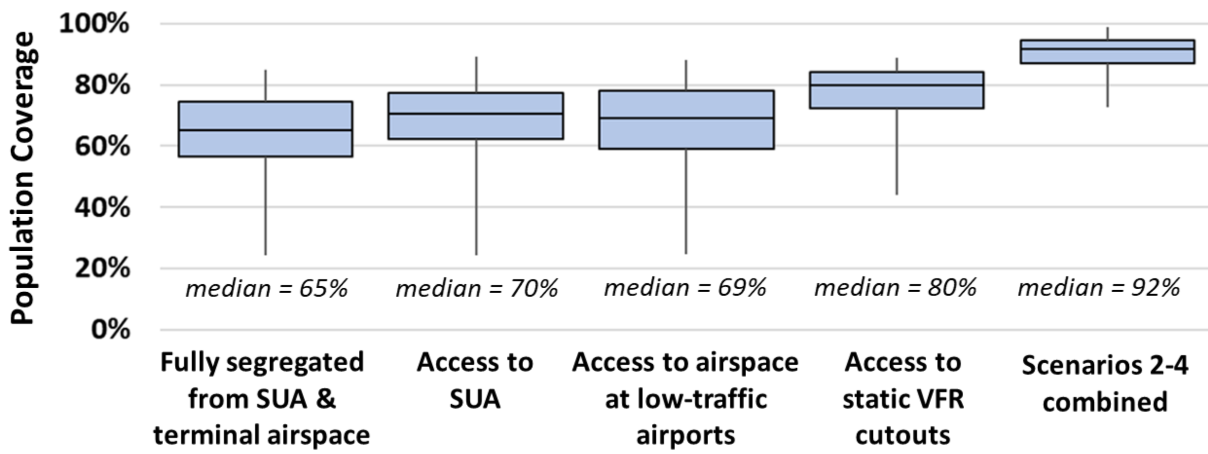


Fig. 88 Population coverage for 34 MSAs in five ATC ConOps scenarios.

The third bar of Fig. 88 demonstrates the impact of UAM access to controlled airspace at airports supporting less than 75,000 total operations per year (or less than 20,000 commercial flights). Five cities, including Philadelphia, Pittsburgh, and Boston, experience an increase in population coverage of 10% or more. However, the general affect across the MSAs is less with a median increase in population coverage of 4% compared to the fully segregated scenario.

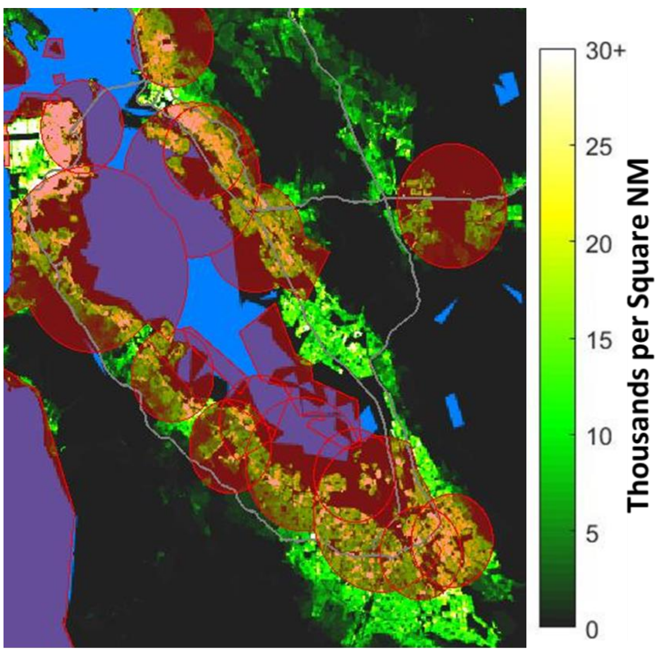
The fourth bar of Fig. 88 demonstrates the potential impact of UAM access to VFR airspace cutouts at high-traffic airports. Under this strategy, cutouts were generated where VFR radar separation was met to 99.5% of conventional aircraft operations in any flow pattern of high-traffic airports. VFR cutouts of this type may increase the median population coverage in the MSAs to 80%. When considering the independent application of the three integration strategies, VFR cutouts provide the most significant increase in population coverage. Furthermore, VFR cutouts are the only strategy to increase population coverage for the MSAs in the bottom quartile.

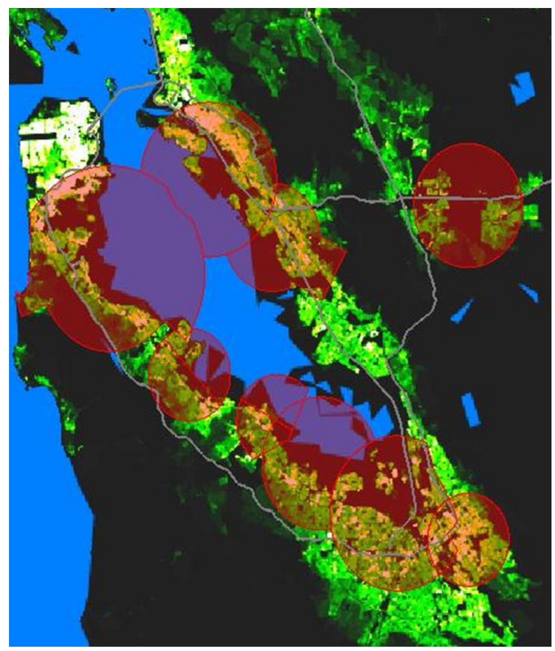
The fifth bar of Fig. 88 displays the potential population coverage in an ATC scenario were the three integration strategies are applied simultaneously and a UAM flight could access SUA, controlled airspace at low-traffic airports, and static VFR cutouts. The result of this scenario is an increase in median population coverage from 65% (in the fully segregated case) to 92%.

Furthermore, the interquartile range and spread of the lower quartile in the fifth bar are substantially reduced. This indicates that the simultaneous application of the three strategies provides a high degree of consistency in population coverage across all of the MSAs. The change in population coverage for the three strategies combined is larger than the sum of the changes for each strategy implemented independently. This indicates that the strategies are complementary to one another and that two or more of the airspace constructs may affect the same surface locations (as often was the case for stadium TFRs and controlled airspace).

Fig. 89 and Fig. 90 use the San Francisco MSA to display the trends introduced in this section.

Fig. 89 displays how mission coverage is affected when UAM is authorized to access SUA. The primary impact on mission coverage is the removal of two stadium TFRs from Berkeley and the San Francisco city center located in the upper left corner of the sub-figures. These TFRs were each associated with baseball stadiums and for up to approximily 100 days a year could impact UAM access to approximately 16% of the region's population and as much as 50% of the long-duration commuter workplaces. ATC impacts on commuter residences and workplaces are discussed more thoroughly in the next section.





Accessible Population: 48%
Accessible Commuter Residences: 57%
Accessible Commuter Workplaces: 24%

(a) Scenario 1: fully segregated from SUA and all controlled airspace

Accessible Population: 64%
Accessible Commuter Residences: 70%
Accessible Commuter Workplaces: 77%

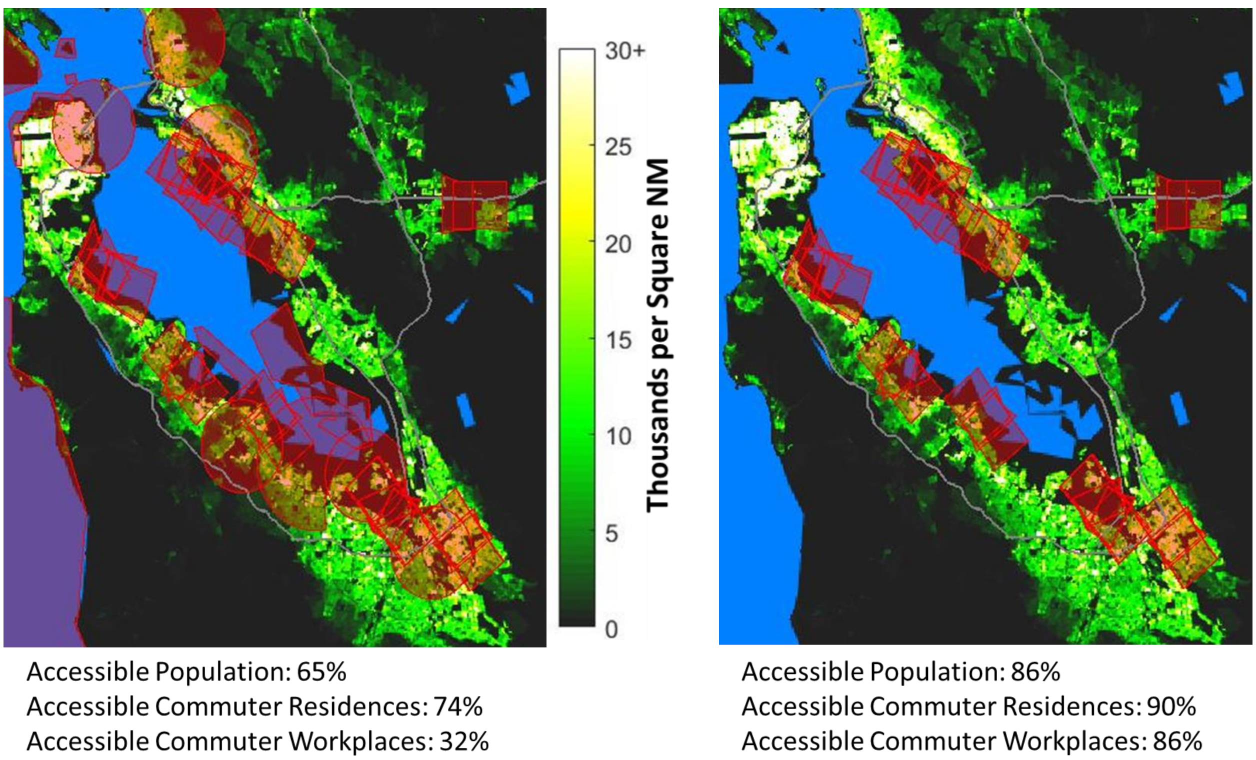
(b) Scenario 2: access to SUA but exclusion from all controlled airspace

Fig. 89 Population coverage in the San Francisco MSA for ATC ConOps scenarios 1 and 2.

Fig. 90 displays the potential benefits of VFR cutouts at high-traffic airports when implemented independently, as well as with the other two ATC integration strategies. Comparing sub-figure (a) of Fig. 90 to those of Fig. 89, the largest different in mission coverage is apparent around San Francisco and San Jose international airports located in the upper left and lower right of the images, respectively. These airports each have large class B airspace volumes. VFR cutouts may provide UAM access to much of the population located within each airspace.

Despite greater access to controlled airspace at high-traffic airports and an increase of population coverage to 65% compared to 48% in the fully segregated scenario, long-duration commuter workplace coverage and 35% of the MSAs population remains within an active airspace construct in this scenario. Sub-figure (b) of Fig. 90 displays how simultaneously allowing access to VFR cutouts, SUA, and controlled airspace at low-traffic airports enables access to over 20% more of the population without ATC interaction than any of the three integration strategies when implemented independently.

Additional visualizations of mission coverage constraints due to ATC for every MSA may be found in Appendix D.



(a) Scenario 4: access to static VFR cutouts but exclusion from SUA and low-traffic airspace

(b) Scenario 5: access to SUA, VFR cutouts, and low-traffic airspace

Fig. 90 Population coverage in the San Francisco MSA for ATC ConOps scenarios 4 and 5.

9.6.3 Comparison of the Influence of ATC on Air Taxi and Commuter UAM Missions

As briefly discussed concerning Table 23 and Fig. 90, the ATC constraint and UAM integration strategies may impact commuter mission coverage differently than the air taxi (i.e., population) mission coverage in a given MSA. These differences are the result of different geographic locations of demand for these two mission types with respect to the various airspace constructs.

Fig. 91 displays a boxplot of mission coverage for each MSA in terms of total population (a proxy metric for the air taxi mission demand) and in terms of long-duration commuter workplaces and residences (proxy metrics for the commuter mission demand). The data presented in Fig. 91 is for a fully segregated ATC ConOps scenario.

Significant variation is apparent in the influence of ATC on each of these three metrics. Mission coverage is highest for induced and existing the long-duration commuter communities (census tracts where greater than 250 people travel 60 or more minutes to work). This is the result of long-duration commuter communities primarily being spread along the periphery of the city center rather than clumped together in downtown areas. The geographic spreading of the communities makes them less likely to simultaneously be restricted due to an overlying airspace construct.

Opposite this trend, the commuter workplaces exhibit a lower accessibility than either the commuter residences or the general population. This results from workplaces tending to be clustered in a single region (such as in a city center or industrial park) where an airspace construct could preclude access to a larger percentage of workplaces simultaneously. Furthermore, workplaces are often clustered in proximity to airports, perhaps due to industrial zoning.

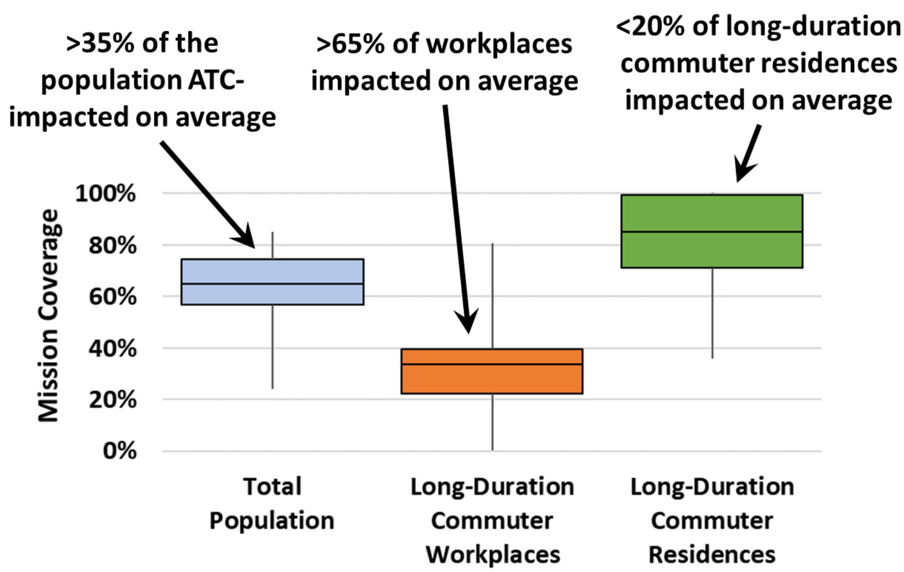


Fig. 91 Comparison of the commuter and air taxi mission coverage metrics for the 34 MSAs under a fully segregated ATC ConOps scenario.

While Fig. 91 displays how the ATC constraint may impact UAM scaling for different mission types under a fully segregated ATC ConOps scenario (i.e., a baseline condition for current operations), the figure does not provide insight into the potential value of the three integration strategies to relieve the ATC constraint for each mission type.

Considering this, Fig. 92 presents boxplots of the commuter and air taxi mission coverage metrics for four of the ATC ConOps scenarios. The ATC scenario concerning UAM access to controlled airspace at low-traffic airports was not shown for brevity as it had a similar impact on mission coverage as the access to SUA integration strategy. Compared to Fig. 91, the long-duration commuter residence metric was further divided in Fig. 92 into existing commuter residences (census blocks with >500 long-duration commuters) and induced commuter residences (census blocks with <500 but >250 long-duration commuters).

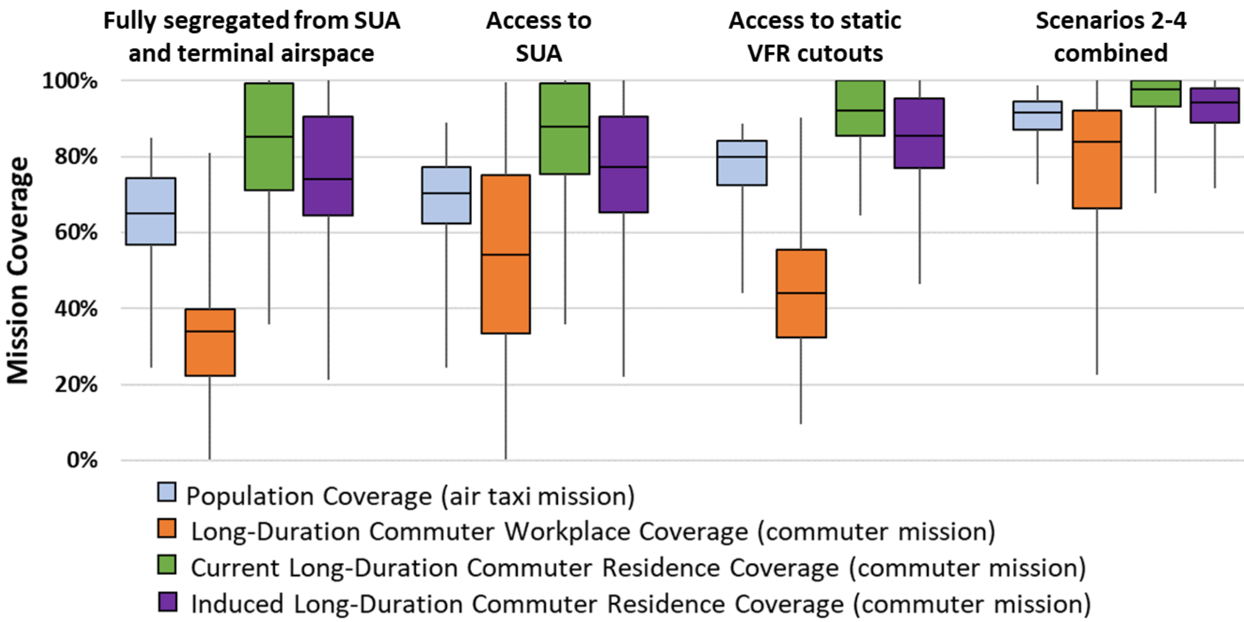


Fig. 92 Comparison of the commuter and air taxi mission coverage metrics for the 34 MSAs under four ATC ConOps scenarios.

The general trends identified in Fig. 91 remain in Fig. 92, namely a lower commuter workplace coverage and higher commuter residence coverage for all ATC ConOps scenarios than the population coverage metric. Current long-duration commuter residence coverage was consistently above induced commuter residence coverage. There were a few differences of note between the ATC ConOps scenarios, however.

For example, access to SUA led to a marginal increase in UAM mission coverage of the general population and both types of commuter residences in Fig. 92 (i.e., a comparison of the blue, green, and purple bars in the two leftmost groupings). However, comparison of the first and second orange box plots in Fig. 92 indicates that the influence of SUA was far more pronounced for UAM services to long-duration commuter workplaces.

As displayed in Table 25, when UAM operations are fully segregated from SUA and controlled airspace they may potentially access a median of 34% of the long-duration commuter workplaces in the MSAs without ATC interaction. If provided access to SUA, then the median service coverage increases to 54%. In some cities, such as Pittsburgh, enabling UAM access to SUA increases workplace coverage up to 100%. SUA are more impactful on workplace accessibility than that of the general population as sports stadiums are frequently located within or near city centers where workplace locations are concentrated.

Table 25. Median mission coverage for the air taxi and commuter mission metrics.

ATC ConOps Scenario	Population Coverage *air taxi mission type*	Long-Duration Commuter Coverage *commuter mission type*		
		Workplaces	**Current Residences**	**Induced Residences**
Fully Segregated	65%	34%	85%	74%
Access to SUA	70%	54%	88%	77%
Access to Low-Traffic Airport Airspace	69%	35%	86%	78%
Access to Static VFR Cutouts	80%	44%	92%	86%
Scenarios 2-4 Combined	92%	84%	98%	94%

Fig. 93 displays the variance of each mission coverage metric in the Columbus, OH MSA when UAM operations are excluded from all controlled airspace. Controlled airspace in Columbus is located exclusively above the city center and may hinder UAM access to 34% of the population and 55% of the workplaces. However, 100% of the existing commuter communities and 91% of the induced commuter communities remain accessible as they reside beyond this central region and are not impacted by controlled airspace.

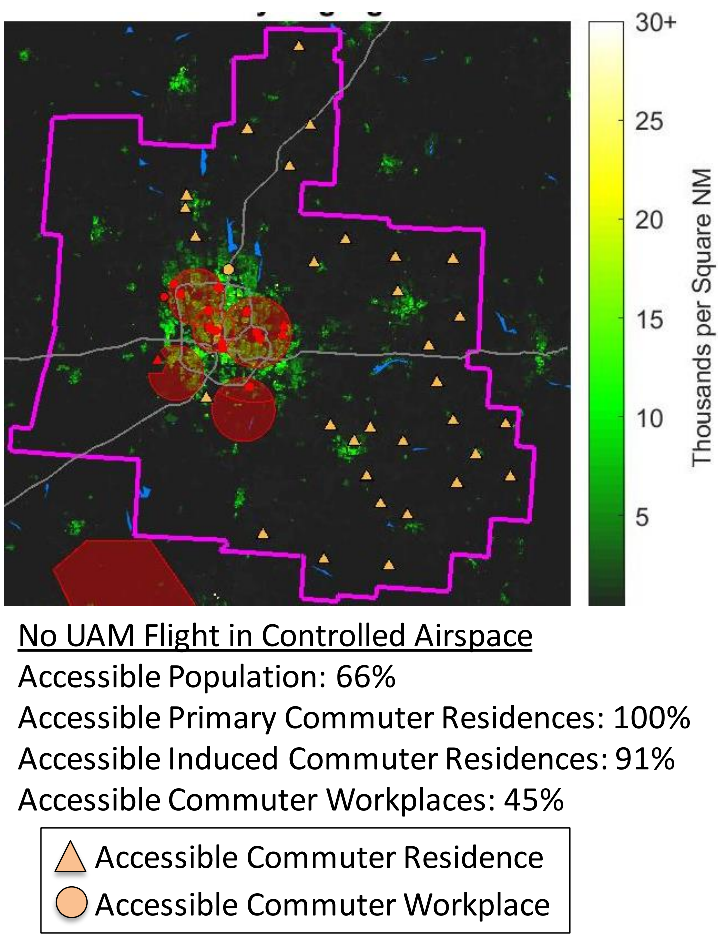


Fig. 93 Comparison of access to populated areas, workplaces, and long-duration commuter residences for the Columbus, OH MSA.

The implication of Fig. 92 and Fig. 93 is that ATC restrictions for UAM scaling may more significantly impact workplace accessibility for commuter missions than the other UAM service types. Furthermore, the air taxi mission may also be disproportionally impacted by the concentration of ATC restrictions in city centers as numerous points of interest (such as sporting arenas and tourist areas) are frequently concentrated in the city center. Sub-urban and rural missions therefore represent the service with the lowest barrier to entry for UAM from an ATC integration perspective.

9.6.4 Comparison of Mission Demand in Each MSA

The previous sections evaluated UAM mission coverage in the 34 MSAs based upon the *percentage* of their total population, long-duration commuter workplaces, or long-duration commuter residences that could be accessed by UAM aircraft under various ATC ConOps scenarios. While comparing mission coverage percentages provided a common baseline with which evaluate differences in the ATC constraint between the MSAs, the total addressable market for UAM is related to the total number of individuals UAM could access in an area.

This section therefore compares UAM mission coverage based on the total population (for the air taxi mission) or the total number of long-duration commuters (for the commuter mission) that may be accessed in each MSA under the various ATC ConOps scenarios.

Table 26 displays the eight MSAs with the largest number of individuals that could be accessed by UAM flights without ATC interaction when UAM may fly in SUA but are excluded from all controlled airspace (including at low-traffic airports). Interestingly, New York City, Los Angeles, and Dallas were MSAs within the bottom quartile of mission coverage by the percentage of their population that could be accessed. However, these three MSAs appear in the top quartile of mission coverage by total number of individuals that may be accessed.

For example, 46% of the population of Los Angeles required ATC interaction to access in this ATC ConOps scenario (the fourth lowest MSA by percentage), but the 54% of Los Angeles that could be accessed without ATC interaction constituted the third largest population by number of accessible individuals in all the MSAs. Even though a larger percentage of Los Angeles' population could not be accessed by UAM without ATC interaction, the comparatively larger size of the MSA's population (the second largest of all the MSAs) resulted in the remaining accessible market being larger than most other areas.

Table 26. MSAs with the greatest number of accessible individuals when UAM aircraft have access to SUA but are excluded from all controlled airspace.

Air Taxi Mission	
Accessible Population (millions)	
New York City	11.1
Chicago	7.3
Los Angeles	6.9
Boston	4.9
Philadelphia	4.2
Atlanta	4.0
Dallas	3.8
Houston	3.8

Commuter Mission - Commuters Travelling > 60 min each way			
Accessible Workplaces		*Accessible Residences*	
New York City	535,000	New York City	887,000
Chicago	249,000	Chicago	344,000
Los Angeles	221,000	Washington, DC	298,000
San Francisco	179,000	Los Angeles	242,000
Atlanta	112,000	Boston	221,000
Washington, DC	105,000	Atlanta	207,000
Houston	100,000	San Francisco	179,000
Philadelphia	83,000	Houston	166,000

Testing a different ATC ConOps scenario, Table 27 displays the MSAs with the largest accessible population when UAM may operate within SUA, controlled airspace at low-traffic airports, and VFR cutouts without ATC restrictions. This scenario is the most aggressive case for UAM integration and results in the highest mission coverage in each MSA.

Once again, all MSAs in Table 27 are comparatively large by population in the data set. Seven of the eight cities with the largest accessible populations remain the same to those from Table 26, although their order is modified slightly. Los Angeles, which was especially constrained by controlled airspace, could potentially access an additional 3.3 million individuals through these UAM integration strategies. In comparison, Chicago only experienced an increase of 1.4 million individuals as the MSA was less impacted by ATC restrictions.

Table 27. MSAs with the largest number of accessible individuals when UAM may operate in SUA, controlled airspace at low-traffic airports, and VFR cutouts.

Air Taxi Mission	
Accessible Population (millions)	
New York City	17.0
Los Angeles	10.2
Chicago	8.7
Boston	7.3
Philadelphia	5.8
Dallas	5.7
Houston	5.5
Washington, DC	5.1

Commuter Mission - Commuters Travelling > 60 min each way			
Accessible Workplaces		*Accessible Residences*	
New York City	1,160,000	New York City	1,431,000
Los Angeles	344,000	Washington, DC	406,000
Chicago	278,000	Chicago	390,000
Washington, DC	261,000	Los Angeles	348,000
San Francisco	201,000	Boston	311,000
Houston	152,000	Atlanta	244,000
Atlanta	146,000	San Francisco	232,000
Boston	120,000	Houston	227,000

The key takeaway of Table 26 and Table 27 is that although smaller cities were found in Section 9.6.1 to generally present fewer ATC constraints for UAM access to their populations, larger cities provide a greater demand opportunity overall. In other words, the market with the largest number of individuals that could potentially be accessed by UAM (i.e., the largest serviceable addressable market) is most strongly driven by the total population of an MSA (i.e. the largest total addressable market) irrespective of the ATC constraints in the region and the ATC ConOps scenario applied.

Fig. 94 and Fig. 95 provide further evidence for this conclusion. The full data sets from which these figures were developed is provided in Appendix D.

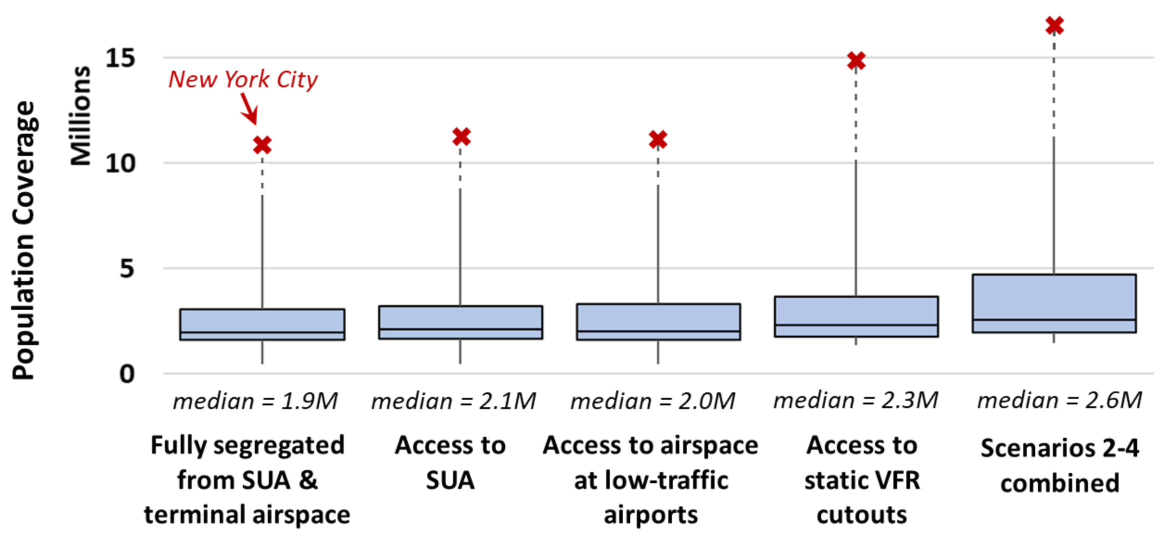


Fig. 94 Box plot of UAM population coverage for 34 MSAs in five ATC ConOps scenarios.

Fig. 94 shows the distribution of UAM population coverage for the 34 MSAs in each of the five ATC ConOps scenarios. The New York City MSA is an outlier for all five scenarios with a significantly larger population that may be accessed by UAM without ATC interaction than the median city. Seven MSAs (New York City, Los Angeles, Boston, Philadelphia, Houston, and Dallas) remain within the top eight cities (i.e., the top quartile) of population coverage for all five ATC scenarios. Atlanta is in the top quartile for all but the fifth scenario where Washington, D.C. replaces it.

Fig. 95 displays the distribution of UAM long-duration commuter community workplace coverage for the 34 MSAs in each of the five ATC ConOps scenarios. The median values for workplace coverage are far smaller than population coverage, and the spread between the median values and the MSAs in the upper quartile is greater. This indicates that some MSAs have substantially larger potential demand for the long-duration commuter mission that may be served by UAM without ATC restrictions. Both the New York City MSA and Los Angeles MSA are outliers in various ATC ConOps scenarios. Six MSAs (New York City, Los Angeles, Houston, Chicago, Atlanta, and San Francisco) remain within the top eight cities of workplace coverage for all five ATC scenarios.

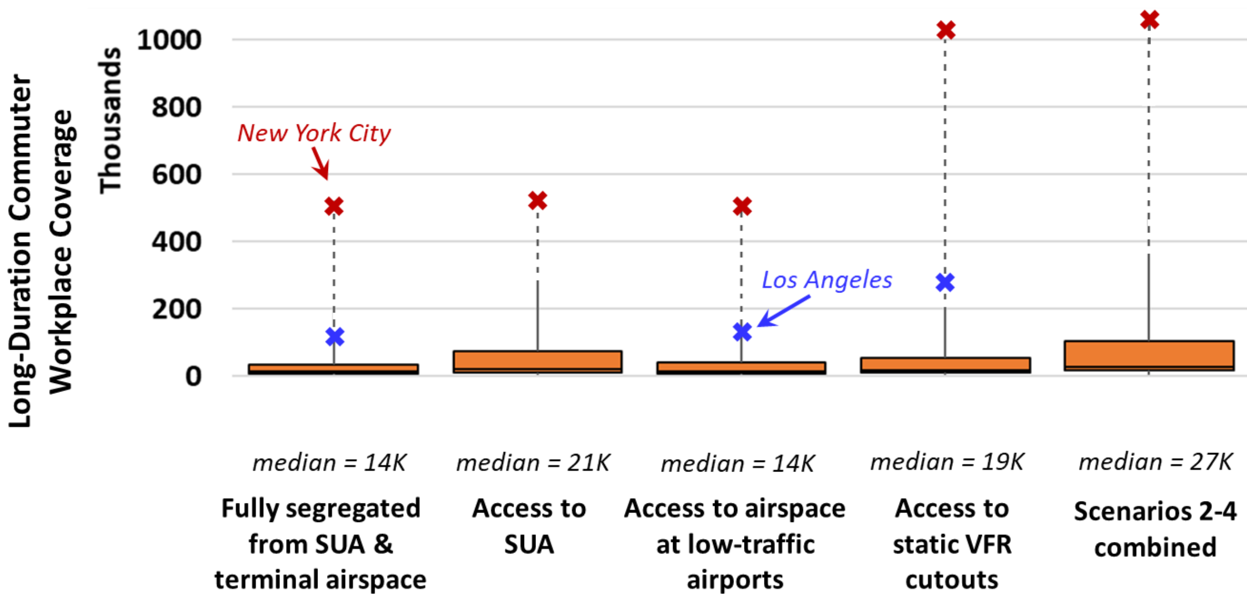


Fig. 95 Box plot of UAM long-duration commuter workplace coverage for 34 MSAs in five ATC ConOps scenarios.

9.7 IFR UAM Operations and MSA Weather Analysis

The ATC integration strategies evaluated thus far in this chapter (i.e., SUA access, access to controlled airspace at low-traffic airports, and VFR cutouts) were anticipated to provide relief from ATC interaction only when UAM operate under VFR. While developments such as NASA's UTM system may ultimately provide an alternative to human controller management of IFR operations, near-term implementation of UAM will be subject to controller workload limitations and larger, IFR radar separation minima when operating in any class B, C, D, or E airspace. These ATC limitations for the scaling of IFR flights would impact nearly every potential UAM market.

Furthermore, even if new developments such as UTM ultimately enable IFR UAM flights within these airspaces without human controller interaction (e.g., through IFR cutouts), IFR radar separation requirements to conventional manned aircraft constitute a substantial restriction for UAM mission coverage in the MSAs.

As means of an example, Fig. 96 displays mission coverage for the air taxi and commuter missions within the 34 MSAs if UAM could notionally operate under IFR in SUA, controlled airspace at low-traffic airports, and static IFR cutouts from controlled airspace at high-traffic airports. The IFR cutouts were modeled in this case to provide three NM of lateral separation or 1000 ft of vertical separation between UAM and conventional arrivals or departures at high-traffic airports in any airport flow pattern. As with the VFR cutouts, UAM aircraft were required to maintain a minimum altitude of 300 ft AGL (note that this modeling assumption does not meet current IFR terrain and obstacle separation requirements of 1000 ft).

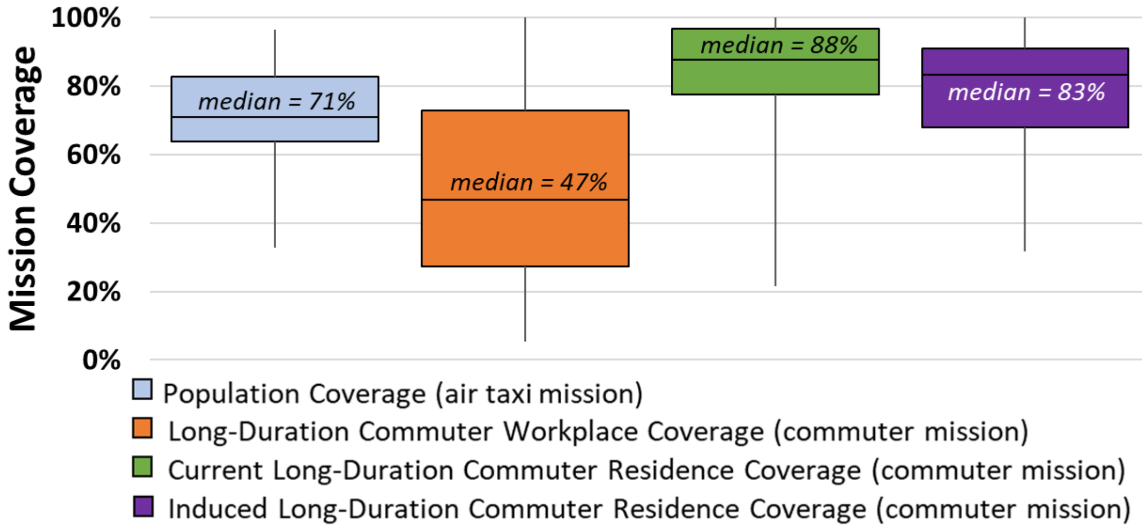


Fig. 96 Mission coverage when UAM aircraft may access SUA, controlled airspace at low-traffic airports, and static IFR cutouts without ATC interaction.

Through a comparison of the first boxplot in Fig. 96 and the fifth box plots in Fig. 88, it may be seen that static IFR cutouts provide significantly less population coverage for UAM in most cities compared to static VFR cutouts. In fact, a number of cities experienced a *reduction* of population coverage from this integration strategy compared to a scenario where flights are excluded from controlled airspace at high-volume airports. The cause of these reductions was that the IFR separation minima prevented UAM access to a larger volume of airspace than contained with the class D airspace around some airports.

Considering the limitations of UAM mission coverage under IFR and the longer-term implementation of systems such as UTM, MSAs that require UAM to operate under IFR less frequently may be attractive early markets for UAM. This section presents a first-pass analysis of the weather conditions within each MSA to identify the frequency of UAM IFR operations.

METAR weather observations were collected from July 1, 2014 through June 30, 2017 at the primary airport in each MSA. Information on visibility, ceiling, winds, precipitation, temperature, and convective action were extracted from the reports as these conditions may influence UAM operations. The following sections discuss the implications for UAM operations from this weather analysis.

9.7.1 Required IFR for UAM

The requirement to operate under IFR is a function of visibility, cloud ceiling, the airspace being operated in, and the type of aircraft being operated. Table 28 summarizes the weather requirements that apply to a part 135 UAM aircraft in order to operate under VFR.

Table 28. VFR weather minima for a Part 135 UAM operation.

Airspace Type	Weather Condition	UAM is a Helicopter	UAM is a Fixed-Wing
Surface-level class B	minimum visibility	½ SM (day); 1 SM (night)	3 SM
	cloud clearance	xlear of clouds	
Surface-level class C, D, or E	minimum visibility	½ SM (day); 1 SM (night)	3 SM
	cloud clearance	500 ft below, 2000 ft horizontal	
Aloft class B, C, D or E	minimum visibility	3 SM	
	cloud clearance	500 ft below, 2000 ft horizontal	
Class G below 1200 ft AGL	minimum visibility	1 SM (day); 3 SM (night)	
	cloud clearance	clear of clouds (day); 500 ft below and 2000 ft horizontal (day)	

A potentially useful implication for UAM operations from Table 28 is that a UAM aircraft classified as a helicopter benefits from reduced visibility requirements compared to one classified as a fixed-wing.

An average of 30% of the population of the 34 MSAs resided within surface-level class B, C, or D airspace where helicopters could use lower visibility minima. Furthermore, class G airspace extends up to 700 ft AGL or higher in most of the densely populated areas of the MSAs. Part 135 helicopters, whose minimum flight floor is 300 ft AGL, could therefore benefit from reduced visibility in this class G airspace before entering or after existing controlled airspace.

METAR weather reporting data were evaluated to determine the percentage of the time that UAM helicopters or fixed-wing aircraft would be required to operate under IFR in each MSA. If a broken or overcast cloud ceiling was reported below 1000 ft, or if vertical visibility was reported below 1000 ft then both helicopters and fixed-wing aircraft were assumed to operate under IFR.

Alternatively, if visibility was less than three miles then fixed-wing aircraft were assumed to operate under IFR. If visibility was less than one mile then helicopters were assumed to operate under IFR. Note that these assumptions were conservative compared to the actual requirements in Table 28.

Fig. 97 summarizes the results. The upper quartile group for fixed-wing aircraft spans from 7.4% to 10% annual IFR frequency. For helicopters the upper quartile group is similar spanning from 6.7% to 9.5% annual IFR frequency. The MSAs in the upper quartile group are mostly located in the Midwest, the mid to north Atlantic coast, and Texas. Boston required helicopter IFR operations most frequently at 10% of the year. San Antonio required fixed-wing IFR operations most frequently at 9.5% of the year.

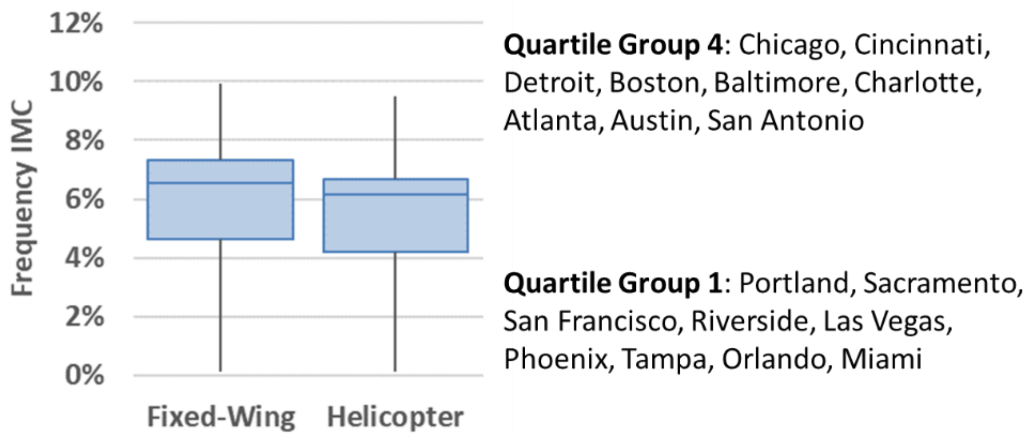


Fig. 97 Distribution of required IFR operations in the 34 MSAs.

The lower quartile groups for both aircraft types span from approximately 0.2% to 4.5% annual IFR occurrence. The MSAs in the lower quartile groups are located in Florida, the southwest, or the west coast. Miami, Las Vegas, and Phoenix required IFR operations 2% of the time or less.

The key takeaways from Fig. 97 for UAM operations are:

- Despite benefiting from reduced visibility minima, helicopters are not able to operate under IFR significantly less frequently than fixed-wing aircraft as low cloud ceilings typically precluded VFR rather than low visibility.
- Cities in the west coast, Southwest, and Florida require the least IFR.
- Cities in Texas, the Midwest, and the mid to north Atlantic require the most IFR.
- The MSAs reported an approximimily 6.6% median (6.0% mean) annual occurrence of IFR conditions for fixed-wing aircraft

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9.7.2 Implications of Weather for the Severity of the ATC Constraint in each MSA

Table 29 displays the frequency with which fixed-wing UAM aircraft would be required to operate under IFR in each MSA. Mission coverage of population is displayed for an ATC ConOps scenario where UAM cannot access SUA or controlled airspace (i.e., fully excluded operations). The MSAs in the upper quartile of population coverage are shaded in blue.

Seven of the eight MSAs with the largest population coverage require IFR more often than the median MSA (a 6.5% occurrence). Three of these MSAs are also in the upper quartile for most frequent IFR. This is the result of many of the nation's largest cities being located on the northeast seaboard which frequently experiences IMC.

While the Boston market is potentially a third larger than the Houston market, it may also require UAM IFR operations nearly twice as frequently. Houston may therefore be a more attractive area for near-term UAM implementation from an ATC constraint standpoint.

Riverside, Miami, and Phoenix stand out as MSAs with low requirements for IFR operations (< 3%), but populations of greater than two million that may be accessed by UAM without ATC interaction. Despite the low frequency of potential IFR operations for UAM, Miami is potentially challenging for UAM operations due to convective weather. Phoenix may similarly be challenging due to high temperatures. Other weather impacts such as these are discussed below.

Table 29. IFR frequency and accessible population by MSA when UAM is excluded from SUA and controlled airspace.

MSA	Frequency of Required Fixed-Wing IFR	Accessible Population (millions)
Boston, MA	10.0%	4.8
San Antonio, TX	9.7%	1.2
Charlotte, NC	9.5%	1.8
Atlanta, GA	8.9%	3.8
Austin, TX	8.5%	1.3
Chicago, IL	8.2%	6.2
Baltimore, MD	8.0%	1.7
New York City, NY	7.6%	10.8
Detroit, MI	7.6%	3.1
Cincinnati, OH	7.4%	1.6
Los Angeles, CA	7.3%	5.6
Philadelphia, PA	7.2%	4.0
Indianapolis, IN	7.1%	1.6
Pittsburgh, PA	7.1%	1.8
Kansas City, MO	7.0%	1.5
Houston, TX	6.8%	3.6
Seattle, WA	6.7%	2.0
Minneapolis, MN	6.5%	2.0
Cleveland, OH	6.4%	1.5
Washington, DC	6.1%	1.9
Denver, CO	5.9%	1.6
St. Louis, MO	5.6%	2.1
Dallas, TX	5.1%	3.6
San Diego, CA	5.1%	1.6
Columbus, OH	4.9%	1.1
Sacramento, CA	4.6%	1.7
San Francisco, CA	4.3%	2.1
Portland, OR	4.2%	1.6
Orlando, FL	3.9%	1.4
Tampa, FL	3.2%	2.0
Riverside, CA	2.5%	2.8
Miami, FL	1.1%	2.3
Las Vegas, NV	0.2%	0.5
Phoenix, AZ	0.2%	2.4

Blue shading indicates MSA in the upper quartile of mission coverage by population

9.7.3 Other Weather Impacts

Other weather factors that may impact the ability of UAM aircraft to fly include convective weather (i.e., thunderstorms), high winds, and extreme temperatures. Fig. 98 summarizes the distribution of these conditions for the 34 MSAs.

Convective weather was reported near the primary airport of each MSA less than 5% of the time for three quarters of the MSAs. However, the three Florida MSAs and Atlanta each experienced convective weather greater than 10% of the time; Miami reported convective weather 19% of the year on average.

Three-quarters of the MSAs also reported winds in excess of 15 kts less than 7% of the year. Low winds minimize passenger discomfort and reduce vehicle performance requirements, most critically for high-wind landings. San Francisco reported winds greater than 15 kts the most frequently at 16% of the year while Boston was next at 11%.

Finally, temperature profiles vary widely between the MSAs. Very high temperatures may challenge electric aircraft thermal management capabilities. Very low temperatures may benefit electric motor performance, but may also be associated with the potential for icing conditions or battery performance reductions. Minneapolis reported freezing conditions the most often at 25% of the year. Phoenix reported temperatures above 100°F the most frequently at 9% of the year.

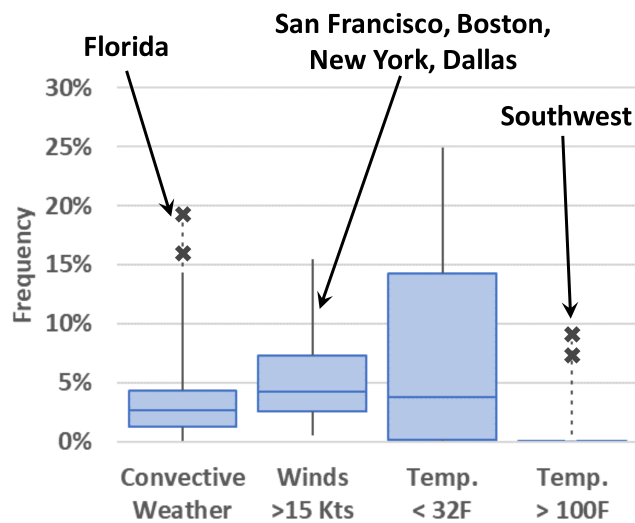

Fig. 98 Distribution of convective weather, high winds, and extreme temperatures in the 34 MSAs.

9.8 Key Findings

The analysis of 34 MSAs provided insight into the severity of ATC limitations for UAM scaling, the effectiveness of different ATC integration strategies, and the variation of these potential ATC limitations with local attributes of an MSA. Key findings from the analysis include:

- Exclusion from controlled airspace is the most significant ATC constraint for UAM mission coverage. Surface-level controlled airspace impacts UAM access to 30% of the population, 46% of long-duration commuter workplaces, and 20% of long-duration commuter residences for the median MSA.
- There is significant variation of the ATC constraint due to local attributes of the MSAs. Controlled airspace impacts UAM access to 76% of the population in Las Vegas, but only 15% of the population in Indianapolis. The number of airports and their proximity to the city center primarily drives these differences.
- Static VFR airspace cutouts are the most effective stand-alone strategy considered in this analysis to relieve the ATC workload constraint. The cutouts are also complemented by other

integration strategies that enable UAM access to SUA and controlled airspace at low-traffic airports. Together, these three ATC integration strategies increase population and workplace mission coverage to 92% and 84%, respectively, for the median U.S. city.

- Enabling access to controlled airspace at airports with less than 75,000 annual operations is a less effective stand-alone relief strategy for the ATC constraint. These low-traffic airports infrequently reside in areas of significant UAM demand.
- SUA intermittently limits access to 10% of the median U.S. city's population and 38% of its workplaces. Washington, DC is an outlier where prohibited airspace permanently excludes UAM access to over 50% of the population and over 80% of the workplaces.
- Long-duration commuter workplace accessibility is generally lower than overall population accessibility due to the frequent location of workplaces near airports, and airports near city centers. Long-duration commuter residences, however, are frequently located on the periphery of cities where they are less impacted by ATC constraints.
- Smaller cities tend to be less restricted by ATC in terms of the percentage of the population or commuter missions that can be covered by UAM. However larger cities dominate in terms of the total number of individuals UAM could potentially serve.
- UAM operation under IFR when provided access to IFR cutouts, SUA, and controlled airspace at low-traffic airports may inhibit access to a median of 29% of an MSAs population due to separation requirements from conventional flights. However, IFR operations are only required with a 6.5% median annual occurrence in the 34 MSAs.

9.9 Conclusion

This chapter evaluated how air traffic control (ATC) services may limit the ability of UAM to serve air taxi and commuter demand in the 34 largest U.S. metropolitan statistical areas (MSAs). Specifically, the chapter addressed the influence of controlled airspace, special use airspace (SUA), and airspace cutouts on UAM mission coverage through four proxy metrics of customer demand.

On average, ATC may influence the feasible scale of *VFR* UAM operations in a given U.S. city in a relatively small percentage of the city's airspace. Furthermore, 65% of an average city's population is anticipated to be accessible to VFR UAM flights without any interactions with ATC. However, the minority of the airspace that is subject to ATC limitations disproportionately overlays dense urban areas, demand "special attractors", and workplace locations. Only 34% of the long-duration commuter workplace locations in the median U.S. city may be served by VFR UAM flights without interactions with ATC. UAM coverage of many long-duration commuter missions requires interaction with ATC and may be scale-limited as a result.

Providing access to SUA, and especially temporary flight restrictions for sporting events, was especially effective to reduce ATC constraints for UAM access to dense urban populations and long-duration commuter workplace locations. UAM aircraft usage of VFR cutouts from controlled airspace was the most effective strategy evaluated in this chapter to relieve the ATC scaling constraint on access to an MSA's population.

IFR operations remained restrictive to UAM mission coverage irrespective of the application of IFR airspace cutouts or other airspace integration strategies reviewed in this chapter. However, IFR operations are only required 6.5% of the year on average in the 34 MSAs.

Finally, the potential impact of ATC on UAM scaling varies significantly between the most restricted and least restricted MSAs. MSAs with large populations tended to have a higher percentage of their potential demand subject to ATC limitations. Despite the greater severity of the ATC constraint in these MSAs, they also offered the greatest potential demand for UAM services due to their large population size. Considering the variation in ATC influence on UAM scaling between cities, city-specific analysis of ATC integration should be conducted to support the development of any UAM mission or market study.

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10 Conclusion

This thesis evaluated the scaling potential for UAM services in major U.S. metropolitan areas. The primary contributions of this thesis are:

1. The proposal of ATC services as a principal scaling constraint for UAM and the estimation of its impact on UAM operations in 34 major U.S. cities.
2. The demonstration of static VFR airspace cutouts as a strategy to substantially relieve the severity of the ATC constraint in most cities for VFR UAM operations.
3. The proposal of four flight procedures to enable UAM arrival or departure at major airports in a manner that is simultaneous and non-interfering with conventional traffic in both visual and instrument conditions.
4. The development of an integer programming approach to model footprint-constrained, UAM takeoff and landing area (TOLA) operations and the use of this approach to demonstrate the critical dependency of TOLA throughput on aircraft turnaround time and ATC separation minima.

10.1 Key Findings

This thesis concludes that:

<u>There are seven high-level scaling constraints for UAM operations.</u>

The feasible scale of UAM operations in a given region was proposed to be limited by: TOLA availability, ATC services, community acceptance, safety and certification of aircraft and operations, pilot availability, network operating logistics, and weather restrictions.

TOLA availability and ATC services in particular were shown to affect UAM operations for nearly all 36 of the reference missions evaluated in the three case study cities. Furthermore, weather restrictions, community acceptance, and network operating logistics impacted UAM scaling by exacerbating the TOLA or ATC constraints. Namely, poor weather conditions increase separation minima and controller workload effectively reducing ATC capacity; communities restrict TOLA development and/or throughput; and network operating logistics depend upon the staging capacity and throughput of footprint-constrained TOLAs and/or ATC throughput capacity in specific airspace.

ATC services and TOLA availability were also uniquely challenging compared to vehicle certification or pilot availability as they vary substantially between different cities. Local factors, including current air traffic, city geometry, and climate, influence the severity of the ATC and TOLA constraints.

<u>The development of static VFR airspace cutouts is a promising strategy to relieve the ATC constraint for VFR operations.</u>

UAM operations within terminal-controlled airspace or special use airspace (SUA) must interact with ATC. Due to limitations of voice-based communications and human cognitive capacity, controller workload may inhibit VFR UAM services to 35% of the population in large U.S. cities on average and as much as 76% of the population in the most impacted cities.

The development of static VFR airspace cutouts from class B, C, or D controlled airspace was shown as an effective strategy to relieve controller workload for VFR UAM operations. VFR airspace cutouts were demonstrated to potentially release over 75% of low-altitude controlled airspace at three major airports without impacting conventional flights. Nationally, VFR airspace cutouts may enable UAM to access up to 92% of the population in the median U.S. city when combined with relief from SUA and access to airspace at small airports with low traffic levels.

Furthermore, VFR airspace cutouts may be implemented with current technologies and regulatory systems. VFR airspace cutouts currently support high-volume helicopter and small aircraft operations. The New York special flight rules area (SFRA) consists of airspace cutouts from multiple class B and C airspace volumes. The SFRA supports tens of thousands of VFR operations per year without ATC limitations. Temporary flight restrictions (TFRs) for security and military purposes exist in nearly every large city and are dynamically activated to exclude some operators from specific airspace. Finally, VFR cutouts may provide a pathway for emerging, automated ATC systems (e.g., NASA's UTM) to be implemented and develop increasingly sophisticated capabilities.

<u>The integration of high-volume UAM operations at or near airports may be supported under IFR or VFR through four strategies.</u>

VFR airspace cutouts cannot support UAM flights directly to most airports due to separation requirements with conventional aircraft. VFR airspace cutouts also cannot support IFR UAM operations. Specific approach and departure procedures are therefore necessary to enable simultaneous and non-interfering UAM access to airports.

Diverging departure procedures may be implemented under current regulations to support IFR or VFR UAM departures at airports. The short runway requirements for VTOL or STOL UAM aircraft ease the development of diverging departures as UAM runways may be developed with a >15° divergence angle from the conventional runways.

UAM arrivals to a TOLA or Point in Space (PinS) located a minimum of 2500 ft from the conventional runways for VFR UAM flights, and a minimum of 9000 ft from the conventional runways for IFR UAM flights, are two existing procedures that can support UAM arrivals at airports. For either of these procedures to be useful for UAM integration, UAM aircraft must conduct an air/hover taxi segment or a visual flight segment from the arrival TOLA/PinS to a gate located at the commercial terminal. Under current ATC policies, only helicopters may conduct air/hover taxiing or PinS arrivals, and air/hover taxiing must be conducted entirely within the airport's physical boundary. These requirements limit the implementation of these procedures at some airports under some weather conditions and runway flow patterns.

Simultaneous Converging Instrument Arrivals (SCIA) and converging VFR arrivals (potentially conducted as land and hold short operations) were proposed as the last strategy to enable high-volume UAM operations at airports. SCIA is advantageous in that it may support UAM aircraft considered either as helicopters or fixed-wing vehicles. However, current procedure design standards require a three nautical mile spacing of SCIA missed approach points which limits the usability of SCIA for UAM integration. Potential reductions of the approach and/or stall speed of UAM aircraft compared to conventional aircraft may enable relief from this procedure design standard and was recommended as an area for future investigation.

TOLA development is a critical constraint for UAM scaling that depends in part on ATC services.

TOLA siting and operations will be most limiting in dense, urban areas due to footprint restrictions, ATC integration, and community acceptance. These challenges are diminished for TOLAs located in less populated areas, and TOLAs located at airports are primarily restricted by ATC integration but have fewer footprint or community acceptance restrictions.

To enable UAM scaling in urban areas, TOLAs must simultaneously have a high throughput capacity to support high-volume flights and a small footprint to ease siting within the urban center. VFR TOLA operations on the order of a hundred flights per hour were found to be feasible from TOLAs that fit within a city block. IFR TOLA operations are significantly more throughput restricted due to increased separation minima, however the four airport integration strategies introduced above may also increase IFR throughput at UAM TOLAs.

To increase TOLA throughput at a footprint-constrained facility, the turnaround time of UAM should be minimized through rapid (or no) charging/refueling, simplified passenger and baggage handling, and minimal taxiing, for example. The inter-arrival time of aircraft (a function of separation minima and aircraft performance) should also be minimized. Furthermore, TOLAs should be developed to support paired or independent arrival and departure operations on multiple runways or landing pads; this capability is also dependent upon separation minima.

UAM mission coverage of potential demand varied significantly between cities due to local differences in ATC and city design

Among the 34 largest metropolitan areas in the U.S., smaller cities tended to have fewer ATC and airport constraints for UAM scaling. However, larger cities represented greater potential demand for UAM despite experiencing more significant ATC constraints. Some specific cities, such as Washington D.C., Las Vegas, and Miami, had unique topological, security, or climate attributes that exacerbated the ATC constraint and limited potential UAM scaling.

If VFR UAM flights were to operate without accessing controlled airspace or SUA (i.e., were fully segregated from conventional ATC), then New York City, Chicago, and Los Angeles represent the largest potential demand for UAM services. However, these cities would also require UAM aircraft to operate under IFR over 7% of the year with a substantial reduction of system capacity due to controller workload and IFR radar separation limitations.

Phoenix, Miami, and Riverside (CA) would require UAM operation under IFR less than 2.5% of the year, but only support UAM access to 15% of the population available in New York, Chicago, and Los Angeles. Initial UAM networks may benefit from operating in cities with fewer ATC constraints and more favorable weather conditions, however long-term scaling of UAM has greater growth potential within larger cities.

Static VFR airspace cutouts and access to SUA reduces the variation of UAM mission coverage between the most and least ATC-restricted cities from 60% to 26%. If implemented, these two airspace integration strategies may lessen the variation of the ATC constraint between cities.

The treatment of UAM aircraft as helicopters by ATC provides significant benefits for UAM operations near or at airports.

Helicopters are afforded special operating rules that reduce controller workload and separation minima for VFR or IFR operations near airports. These special operating rules are based upon the unique flight performance of helicopters, such as their ability to hover. Under current ATC policies, UAM aircraft treated as fixed-wing aircraft would not receive these benefits. Note that UAM aircraft *should not* be considered as helicopters from a pilot rating perspective as this would exacerbate the pilot availability constraint.

Under current regulations and policies IFR operations will be infrequently required for UAM but will prevent high-volume UAM operations in cities when in effect.

When UAM aircraft operate under IFR, large lateral separation minima may inhibit simultaneous operations at TOLAs or on flight routes located in proximity to one another. Furthermore, IFR operations also reduce aircraft throughput at a given TOLA or on any given route due to large longitudinal separation. Despite these limitations, IFR separation requirements were anticipated to have a minimal effect on UAM operations for some cities and missions.

First, the frequency of UAM IFR operations varied significantly in different cities. Of the 34 largest metropolitan areas in the U.S., IFR UAM operations would be required for UAM on average 6% of the year. Nine cities required IFR less than 4% of the time, and three cities required IFR approximately 1% of the time or less. IFR restrictions to UAM operations may therefore be infrequent in some operating areas.

Second, only flights to city centers or airports were anticipated to be constrained by IFR separation minima. TOLAs located in sub-urban or rural regions may be sufficiently spaced to support simultaneous IFR operations. Furthermore, UAM aircraft regarded as helicopters by ATC are afforded special operating rules that may enable them to avoid the application of IFR separation minima at low altitudes in nearly all circumstances. TOLAs and flight routes within city centers, however, will likely be closely spaced to one another; the close spacing of UAM operations in urban areas is incompatible with current IFR separation minima.

Providing UAM flight access to Special Use Airspace (SUA) will signifyingly benefit operations in many cities.

SUA intermittently impacts access to 10% of the population and 38% of the long-duration commuter workplaces on average in large U.S. cities. SUA for sporting events disproportionally exclude access to workplaces, as stadiums are often located within downtown areas. However, stadium SUA are only active intermittently up to a maximum of approximately 400 hours across 85 days a year. Washington DC is a special case where a large, prohibited airspace permanently excludes UAM access to the majority of the region.

10.2 Limitations and Future Work

Urban air mobility is an ambitious new mode of transportation that requires the simultaneous development and implementation of multiple component systems. Furthermore, the vision of UAM largely remains in the conceptual phase of development with new aircraft just now beginning to reach experimental aircraft status, new ATC systems being trialed for small unmanned aircraft, and architects and developers iterating on potential TOLA designs.

As a result, there is significant uncertainty concerning vehicle performance capabilities, markets, infrastructure capacity, community acceptance, and customer demand, among other factors. Recognizing this, the approach taken in this thesis was to evaluate the generic concept of operations for the UAM mission, derive as much information as possible from first principles, remain technology agnostic where possible, and draw results based on general trends and case examples.

The findings of this work are limited by the fidelity of the analyses conducted and the simplifying assumptions made. There is a wealth of future work to build off this thesis and refine our understanding of UAM as follows.

10.2.1 The Community Acceptance Constraint

Community action as a result of aviation noise and safety concerns has historically limited helicopter services in urban areas and even affected transport jet flights at major airports [148,149]. Furthermore, the "Not In My Back Yard" attitude, or NIMBYism, has become more prevalent with rising wealth and environmental awareness making the development of new transportation infrastructure increasingly challenging [150].

This thesis proposed community acceptance (especially of aircraft noise) as an operational constraint that impacts where TOLAs may be located and how they may operate. However, a detailed investigation of community acceptance was not within the scope of this thesis.

Considering the conclusion of Chapter 5 that high-throughput, small-footprint TOLAs are operationally feasible for VFR UAM operations, community acceptance may be the most critically limiting factor for TOLA development in dense urban areas. Appendix A provides a summary of the community acceptance constraint and summarizes the significant body of literature surrounding on this topic. Future work should evaluate what vehicle, infrastructure, operational, or public relations opportunities exist to mitigate the negative influence of community acceptance on TOLA development and operations.

10.2.2 ATC Technologies

This thesis concluded that the legacy ATC system will constrain UAM scaling primarily due to controller workload and separation minima. A number of potential technologies and strategies were introduced that may alleviate these constraints, however detailed analysis and development must be conducted to confirm the perceived benefits and present the safety case to bring the technologies to bear.

In terms of controller workload, further investigations should develop the ConOps to manage UAM (and potentially UAS and GA) operations within IFR and VFR airspace cutous. Ensuring small aircraft conformance with the cutouts will be key. New decision support technologies for pilots and controllers, or potentially autonomous systems, may be enabling capabilities for high-volume cutout operations. In this vein, dynamically allocated cutouts are especially intriguing and require additional research into achievable vacate times for aircraft and real-time situational awareness for pilots and controllers.

Furthermore, initial studies by NASA indicate that reduced communications strategies may significantly increase the number of UAM aircraft a controller may support [97]. Technologies and concepts to enable this outcome should be pursued as a near-term strategy to support increased volumes of UAM operations. These capabilities would complement the airspace cutout approach.

Reducing the IFR separation minima is essential to unlock high-volume UAM services in IMC. When required, IFR separation to conventional aircraft operations limit UAM access to about 30% of a city's population, on average. Furthermore, IFR lateral and in-trail wake vortex separation minima limit UAM throughput to TOLAs.

The challenge of reducing separation minima is twofold. First, research is necessary to develop CNS equipage that can safely enable flight in close proximity to other aircraft without pilot-applied visual separation or extensive controller trajectory conformance monitoring. Second, and perhaps more challenging, the safety case of these systems must be made such that that FAA may take credit for CNS improvements. As an indication of the importance of this second challenge, the surveillance accuracy of modern radar systems and global positioning systems is an order of magnitude better than that of the systems in the 1950's. However, the IFR radar separation minima are by-and-large identical to those of the 1950's despite this technological improvement [151]. This is a rich area for future research will all the trappings of non-technical constraints.

Finally, increasingly automated or autonomous air traffic control and piloting systems offer the potential to alleviate many aspects of the ATC constraint (as well as the pilot availability constraint). These systems are under intense development by NASA and dozens of industry and academic entities but continue to represent a high-impact area for future research.

10.2.3 Demand Analysis

The impact of the ATC constraint was presented in terms of mission coverage of potential UAM demand in Chapter 9. The process used to estimate this potential demand included a number of limitations that naturally lead to future improvement opportunities as discussed below. Furthermore, applying estimates of consumer willingness to pay and UAM service costs to the analysis presented in Chapter 9 would enable formal market studies and service scale estimations.

This first limitation of the mission coverage analysis is that the commuter analysis did not identify flows from a specific origin to a specific destination, but rather identified origins from which a certain threshold of individuals traveled more than 60 minutes to any destination, and vice-versa. This analysis approach is unable to identify specific routes that would be demanded for UAM services. Future work may extend this approach to assess specific commuter flows.

Second, the Census Transportation Planning Product (CTPP) did not provide long-duration commuter workplace location by census tract, but only by census place. The resolution of the identified workplace locations was therefore rather crude, and the assumption that that long-duration commuter workplaces were evenly distributed with all commuter workplaces may have introduced error. Future work may improve the estimation of accessible UAM markets by using data with more resolved workplace locations, such as the LEHD Origin-Destination Employment Statistics (LODES) dataset or cell phone tracking data. LODES also provides higher fidelity estimation of low-volume trips [152].

Finally, this thesis evaluated potential UAM mission coverage solely based upon the geometry of the overlying airspace and conventional aircraft operations. If controlled airspace or SUA extended to the surface, or if separation from conventional aircraft would require UAM flight below 300 ft AGL, then potential demand in those regions was assumed to be inaccessible to UAM without ATC interaction. In reality, customers could use surface transportation to reach TOLAs located outside inaccessible regions. Aircraft may also air taxi or conduct arrival and departure flights at lower altitudes than 300 ft AGL into these regions.

Future work may more rigorously model market access by considering first and last-mile travel time as part of the full UAM trip. Furthermore, future work could determine the probability that a UAM aircraft could or could not enter a potentially inaccessible airspace at a given moment considering controller workload and conventional traffic activities.

10.2.4 City to City Variance in UAM Scalability

The potential scalability of UAM systems was found to vary dramatically from city to city. For example, ATC may limit UAM access to over 75% of the population of Las Vegas and only 15% of the population in Indianapolis. Furthermore, the frequency of instrument conditions varied between 0.17% in Phoenix to nearly 10% in Boston. Finally, numerous hyper-local factors such as zoning laws, community perception of aircraft, and building densities may influence the development of TOLAs [42].

The implementation of UAM in a given city will ultimately require a more detailed analysis of the specific attributes of that city than was evaluated in the review of the 34 metropolitan areas in this thesis. The work presented in this thesis provides a first-pass ranking of cities for their attractiveness to UAM from an ATC perspective. Future work may seek to expand upon these findings and evaluate the scaling potential for UAM in a given city in greater detail.

10.2.5 Stochasticity of UAM Operations and Network Stability

A final limitation of this thesis is that UAM flight operations were assumed to be deterministic in the TOLA throughput analysis. This modeling choice resulted from the intention of the analysis to provide an upper-bound estimation of feasible UAM throughput at TOLAs. Furthermore, deterministic modeling supported the clear identification of the sensitivity of throughput capacity to the TOLA operational and design variables.

However, aircraft operations are not deterministic. The tightly scheduled operations defined by the integer program to maximize TOLA throughput in Chapter 5 may be disrupted by delays or off-nominal operations. Not only would such stochasticity result in a reduction of throughput, but it may also result in a reduction of safety. Furthermore, a deterministically optimized system may create a network stability risk where delay in one component of a tightly schedule network propagates to other areas compounding the total delay of the network.

Future work may investigate how TOLA operations, or UAM flight scheduling in general, are susceptible to stochastic factors. Scheduling algorithms may be developed to provide a sufficient level of network stability through resilience to off-nominal operations. Unlike the systems currently developed for ride-sharing automobile networks, the result of delay or off-nominal operations by an aircraft is not simply lost time and revenue, but also a potential reduction of safety.

10.3 Closing Thoughts

This thesis was submitted 50 years after the authors' research group at MIT published a report titled "Concept Studies for Future Intracity Air Transportation Systems." In this report, students from two generations prior asked the same research questions, viewed helicopters in the same way eVTOLs are viewed today, and conducted variations of many of the same analyses presented in this thesis.

In acknowledgement that there is much to learn from history in order to bring about our bold visions today, this thesis closes with an observation (or perhaps a warning) from its intellectual forebearers [12]:

> *To bring a technically sophisticated new transportation system into existence requires intelligent cooperation between manufacturers, operators, airport owners, and the public as represented by various agencies of federal and local governments. Cooperation in developing new heliports, new IFR air traffic control systems, in obtaining good procedures in and around existing airports, etc. is necessary for several years before the new system reaches a point of maturity and can become economically viable. In the helicopter program, these developments did not occur.*

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Appendix A: Overview of the Community Acceptance Constraint

Aircraft and helicopter noise is one of the most contentious community relations issues for aviation activities. While privacy, health, viewshed, pollution, safety, class segregation, and other factors may also concern communities and affect community acceptance, aircraft noise and its associated quality of life impacts has recently driven significant political and legal community action and is the primary driver of the community acceptance constraint [153,154].

Community opposition of aircraft operations may result in a variety of operational limitations for UAM systems. First, landowners may in some cases take direct legal action against flight above or near their property if a flight diminishes the use and enjoyment of their land. Ref. [42] provides a detailed discussion of the legal pathways and precedents through which individuals may seek compensation from or otherwise limit low altitude overflights.

Second, the FAA may require more strict noise certification requirements (typically in the form of maximum noise generation limits for specific flight modes) through CFR Title 14 Part 36.

Third, community acceptance is an influence factor for both the ATC scalability and ground infrastructure availability constraints. This means that poor community acceptance may trigger the ATC or infrastructure constraints. Table 30 presents a summary of the limitations a UAM aircraft or TOLA operator may experience as a result of the aircraft noise and community acceptance constraint.

Table 30. Potential limitations from the noise and community acceptance constraint.

On Operators	On TOLAs (infrastructure)
Legal action against overflight of property	Limits to new construction or expansion
Geofencing or restriction of airspace	Closure of existing TOLAs
Required noise abatement procedures	Curfews (limited operating hours)
Noise charges or fees	Noise level limitations
More strict CFR Title 14 Part 36 noise certification requirements	Maximum operational quotas
	Loss of local, state, or federal funding

Examples of aviation operational restrictions due to noise abound. The implementation of Performance Based Navigation (PBN) approach and departure procedures, which concentrate flights on precisely defined trajectories, has led to high-profile community action in Boston, Charlotte, Phoenix, and Baltimore, among other cities. This action in some cases has caused local and national authorities to redesign or roll back the PBN procedures. Similarly, decades of community action against jet noise in Los Angeles has led to runway length reductions and the scheduled closure of Santa Monica airport. Finally, annoyance from helicopter overflight and noise led Congress to direct the FAA to reduce noise impacts in Los Angeles in 2013 [62], and prompted the New York City Council to reduce the number of helicopter tours by half in 2017 by prohibiting 30,000 annual flights [63].

Numerous UAM researchers and developers have highlighted noise generation as one of the greatest threats to the implementation of large-scale UAM operations in the United States and a key development goal of UAM aircraft [5,31,43,155]. To address this threat, emerging electric propulsion architectures have been promoted as a means to significantly reduce vehicle source noise through the removal of combustion engines and the utilization of distributed rotors. However, initial psychoacoustic tests performed by NASA suggested that listener annoyance may increase with the number of propellers on an aircraft in a statistically significant manner [57].

Rather than relying solely upon vehicle technologies to reduce noise emission and resultant community annoyance, Ref. [156] conducts an extensive review of the state of the art in aircraft noise prediction and suggests that effectively reducing aircraft noise annoyance requires a balanced approach that addresses noise through several means, namely:

- Noise reduction at the source through engine and airframe technologies
- Noise reduction through operations such as low noise procedures and trajectories
- Noise reduction at the destination through compatible land use and urban development
- Noise reduction through operational restrictions such as flight quotas, noise limits, or curfews

Significant progress has been made in many aspects of this balanced approach. Jet aircraft source noise has been reduced by half since their introduction. Noise abatement procedures have been implemented at many airports. Most major airports have provided noise insulation of residences near airports. Finally, many helicopter pilots have adopted fly neighborly best practices.

However, despite this progress aircraft and helicopter noise continues to be a leading challenge for community acceptance of aviation activities.

Mapping of Aircraft Noise to Operational Restrictions for UAM

Previous literature was reviewed in order to identify the mechanisms through which aircraft flight affects community annoyance. The term "annoyance" describes "all negative feelings such as disturbance, dissatisfaction, displeasure, irritation, and nuisance" towards an aircraft operation [157]. Annoyance is not synonymous with acceptance as will be discussed.

In the literature, the most frequently discussed negative impacts of aircraft noise are:

- Speech Interference: aircraft noise may degrade ability to carry out normal speech [154,158]
- Sleep Disruption: nighttime indoor noise levels have been found to influence awakenings and quality of sleep [154,159–162]
- Fear/Startle: low level flyover, loud flights, or a rapid onset of aircraft noise may lead to sudden fear (startle) or enduring fear of operations [154,163–167]
- Health Impacts: long-term noise exposure has been found to increase the risk of hypertension, cardiovascular disease, and stroke as well as reduce cognitive performance [168–171]
- Economic impacts: aircraft noise may reduce the value, usefulness, or enjoyment of property

It is evident that many of these negative impacts and the annoyance caused by aircraft noise are not solely dependent upon the acoustic nature of the noise generated. Take sleep disruption, for example. Certainly, the sound pressure level and pitch of the sound influences sleep disruption (through an acoustic mechanism). But it is also reasonable that nighttime or early morning flights are more likely to cause sleep disruption in the summer when bedroom windows are open (through a non-acoustic, situational mechanism), or that large jets that cause low frequency vibrations in the home may also increase awakenings (through a non-acoustic, tactile mechanism).

Table 31 presents the results of a literature scan to identify non-acoustic factors (referred to recently as "virtual noise" [73]) that may influence an individual's annoyance to aircraft noise.

The first column lists the identified non-acoustic factors and groups them by the broad mechanisms through which they were perceived to influence community annoyance. The second column indicates the "significance" of each factor. A "negligible" significance was assigned to those factors that were shown in the literature to have no statistically significant effect on noise annoyance. A "low", "moderate", or "high" significant was assigned based upon how strongly the factor was found to influence noise annoyance in the literature.

The third column identifies whether or not the factor was anticipated to affect the probability that an individual will engage in public action against the aircraft generating the noise. This assignment was conducted based upon the opinion of the author with verification from the literature where available. The final column lists studies from the literature scan that discussed the factor, provided statistical analysis of the significance of its impact, or discussed how it may influence the probability of public action.

The purpose of the literature scan was to identify non-acoustic factors that have been found in the literature to have a "high" or "moderate" significance in predicting an individual's annoyance to aircraft noise. These factors were hypothesized to represent they key non-acoustic community acceptance mechanisms. Previous researchers have proposed that these non-acoustic factors may be equally or even more important than the acoustic attributes of aircraft noise in influencing community acceptance [73,172].

From Table 31 it may be determined that all the factors presented, except those in the "demographics" sub-category, have moderate or high significance. Based upon this finding three non-acoustic mechanisms were defined to describe "situational factors", "listener factor", and "secondary effects", respectively.

Furthermore, the author proposes another non-acoustic community acceptance mechanism concerning "privacy" factors. A majority of the historical noise annoyance literature reviewed large, commercial aircraft operations with few general aviation or helicopter flights. Therefore, privacy concerns of low altitude flights may not have been identified as a contributor to annoyance. However, UAM operations will be operating at lower altitudes and may accentuate annoyance to noise due to privacy concerns.

Table 31. Literature survey of non-acoustic factors that influence noise annoyance.

Non-Acoustic Factors in Noise Annoyance		**Significance**	**Expected to Affect Public Action?**	**Reference**
Situational Factors Mechanism	Noise Insulation	moderate	No	[160,161,164]
	Time of Day	high	No	[157,160,162,163,173,174]
	Day of Week	moderate	No	[173]
	Weather	moderate	No	[157,173]
	Ambient Noise	moderate	Yes	[160,174–176]
	Public and Political Profile	high	Yes	[173,175]
Listener or Community Factors Mechanism	*Attitudes*			
	Fear related to noise source	high	Yes	[164,165,177,178]
	Belief that noise situation will worsen	moderate	Yes	[178]
	Belief noise source is valuable to community	moderate	No	[164,177,178]
	Familiarity/adaptation	high	Yes	[158,161,175,178]
	Personality Traits			
	Noise sensitivity	high	No	[164,165,177,178]
	Anxiety/neuroticism/emotionality	moderate	No	[172]
	Control and coping capacity	moderate	Yes	[178]
	Trust in authorities and perceived fairness	high	Yes	[164,178]
	Demographics			
	Age	low	Yes	[157,165]
	Gender	negligible	No	[164,165,175,177]
	Socio-economic status	negligible	Yes	[164,165,177]
	Income	negligible	Yes	[164,165,177]
	Education level	negligible	Yes	[164,165,177]
	Homeownership	negligible	Yes	[164,165,177]
	Marital status	negligible	No	[164,165,177]
	Type of dwelling	negligible	No	[164,165,177]
	Dependency on noise source	negligible	Yes	[164,165,177]
	Use of the noise source	negligible	Yes	[164,165,177]
	Length of residence	negligible	Yes	[164,165,177]
Secondary Effects Mechanism	Correlation of noise to air quality	moderate	No	[164]
	Correlation of noise to dust	moderate	No	[164]
	Correlation of noise to fumes	moderate	No	[164]
	Vibrations due to low frequency noise	moderate	Yes	[179]

Fig. 99 displays how each of the four non-acoustic mechanisms and the single acoustic mechanism translate aircraft operations into noise annoyance, and then annoyance into community acceptance. Furthermore, the two public action pathways through which communities may levy operational restrictions upon aircraft operators to reduce noise are shown in black. These pathways represent community abilities to take legal action against UAM operators directly or foster regulatory change at the local, state, or national level.

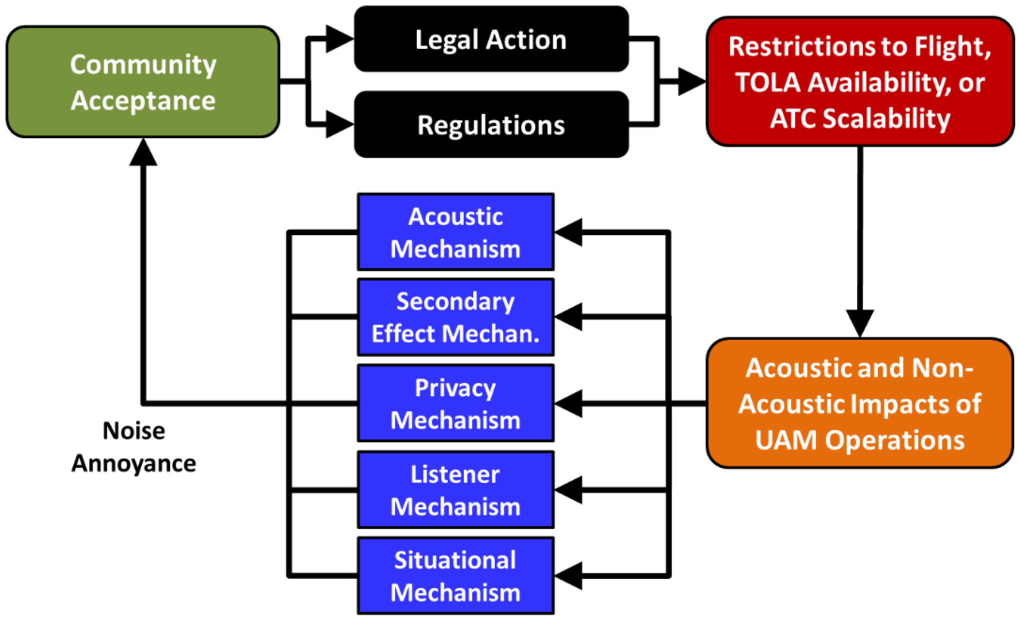


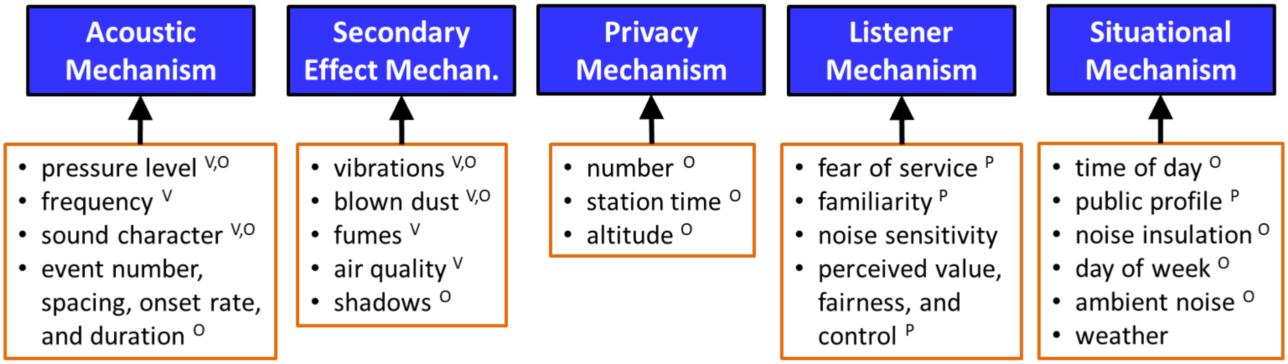
Fig. 99 Noise and community acceptance influence diagram.

The community acceptance influence diagram in Fig. 99 was formulated as a feedback loop. This structure captures the dynamic nature of the community acceptance constraint. More specifically, the "acceptable" level of noise to a community and the resultant constraint severity (level of limitation) for operators is an equilibrium state in the feedback loop.

A second important consequence of the feedback structure is that in order for aircraft noise to result in operational restrictions, not only must the annoyance mechanisms (represented in blue in Fig. 99) be activated, but the public action pathways (represented in black) must also be activated. In other words, even though the acoustic and non-acoustic impacts of UAM operations may result in noise annoyance and adverse community acceptance of the operations, unless those community members engage in public action through legal or regulatory means no restrictions for UAM operations may manifest.

Fig. 100 decomposes the "acoustic and non-acoustic impacts of UAM operations" block from Fig. 99 into greater detail to reveal the fundamental influence factors that act through the mechanisms to determine community acceptance. A majority of the secondary effect, listener, and situational influence factors were drawn directly from the literature as indicated in Table 31. The privacy mechanism influence factors are proposed by the author. The acoustic mechanism influence factors were drawn from Refs. [65], [63], and [67].

Fig. 100 also displays how many of the influence factors may be impacted by noise mitigation efforts in vehicle technologies (^{V}), operations (^{O}), or public relations (^{P}). Two influence factors, namely the inherent noise sensitivity of an individual and the weather conditions of the flight, were determined to be independent of the UAM operator and no viable approaches exist to mitigate their influence on annoyance.



V – vehicle design dependence: vehicle technologies may be used to reduce the impact of this factor
O – operational dependence: vehicle ConOps may be adjusted to reduce the impact of this factor
P – public relations dependence: the relationship between the UAM operator and community may reduce the impact of this factor

Fig. 100 UAM influence factors on noise annoyance with indicated dependencies upon vehicle technologies, operations, or public relations.

Discussion of Noise Annoyance Mechanisms

Each of the identified mechanisms that affect noise annoyance from UAM operations are discussed in brief in the follow sub-sections. The reader is referred to the extensive literature on annoyance presented in Table 31 for a detailed discussion of each influence factor presented in Fig. 100.

1. Acoustic Mechanism

The acoustic mechanism captures the audible aspects of noise and the impacts they have upon annoyance. Much of the existing annoyance literature is focused upon the various acoustic influence factors. Furthermore, the traditional aircraft noise metrics such as Day Night Level (DNL), Effective Perceived Noise Level (EPNL), and Sound Exposure Level (SEL) are also nearly entirely based upon acoustic influence factors. Noise is typically found to be more objectionable through the acoustic mechanism due to the following influence factor qualities:

- it is louder (higher sound pressure level)
- it has a frequency between 2-5 kHz corresponding with human ear sensitivity [180]
- the character of the sound is impulsive (such as helicopter blade slap) [177], sharp (few low-frequency tones), rough, or exhibits strong tonality such as pure tones or a buzzsaw effect [172]
- the number of events, their duration, the spacing between them, and the onset rate at which their sound level increases is displeasing

Numerous vehicle technologies (including distributed electric propulsion architectures) and operational changes have been promoted as potential approaches to reduce annoyance through the acoustic influence factors [4,43,92].

2. Secondary Effect Mechanism

The secondary effect mechanism describes the role that non-auditory sensory impacts of aircraft operations may have on influencing annoyance. One of the primary effects of these factors is to alert individuals to the presence of aircraft even when they would not have been aware of flight through audible means (such as if the flight sound was masked by ambient noise levels).

For example, indoor vibrations due to the low-frequency sound components of large jet engines commonly alert individuals to an aircraft's presence, especially at night, triggering a noise concern and annoyance [179]. Electric aircraft technologies are anticipated to eliminate the "vibrations", "fumes", and "air quality" influence factors. Operational considerations may address impacts from shadows and blown dust.

3. Privacy Mechanism

Although not a mechanism traditionally discussed in the annoyance literature, privacy concerns have led to legal action against low flying helicopters and aircraft in court cases including *Dow Chemical Co. v. United States* (476 U.S. 227, 229), *California v. Ciraolo* (476 U.S. 207), and *Florida v. Riley* (488 U.S. 445). Furthermore, privacy concerns have been identified as a significant community acceptance issue for emerging UAS operations [181].

The author therefore proposes that UAM operations, which will frequently occur in low altitude airspace, may accentuate noise annoyance as a result of individuals' discomfort with the proximity of the flights from a privacy standpoint. The influence factors expected to affect the privacy mechanism are the number of flights that occur over an individual, their station time above that individual (transit or holding), and the altitude at which the overflights occur. These influence factors are nearly entirely dependent upon operational decisions by the UAM operator.

4. Listener Mechanism

The listener mechanism describes numerous qualities of the individual listener (or community of listeners) that have been shown to influence their annoyance to aircraft noise. These influence factors include a fear of the service that an individual may hold. Fear could be the result of an awareness of previous accidents, a lack of understanding of the technology, or an innate discomfort with the characteristics of overflight.

Similarly, a person's familiarity and previous experience with UAM operations, how they perceive the value of the flights for their community, the fairness with which the noise is distributed, and the level of control which they or local community leaders have over the flights directly influence their annoyance with the operations. All three of these influence factors may be impacted through the UAM operator's relationship with the individual or community.

The fourth influence factor, the inherent noise sensitivity that an individual expresses, may cause some individuals to be annoyed while others are not. The UAM operator does not have a pathway to influence this final factor [164,172].

5. Situational Mechanism

The situational mechanism describes qualities of the environment in which the noise was generated, through which it propagated, and in which it was received. For example, the "time of day" influence factor captures the trend that nighttime, early morning, or evening operations are typically found to be more annoying than business hour operations. Similarly, weekend operations, operations in mild weather, and operations in areas with low ambient noise levels are all likely to increase annoyance to aircraft noise as individuals are more likely to be outside, have windows open, or be engaged in recreational activities.

All of the situational influence mechanisms, except the weather conditions, are anticipated to have potential operational or public relations mitigation pathways for UAM operators.

Appendix B: Airport Transiting Topologies

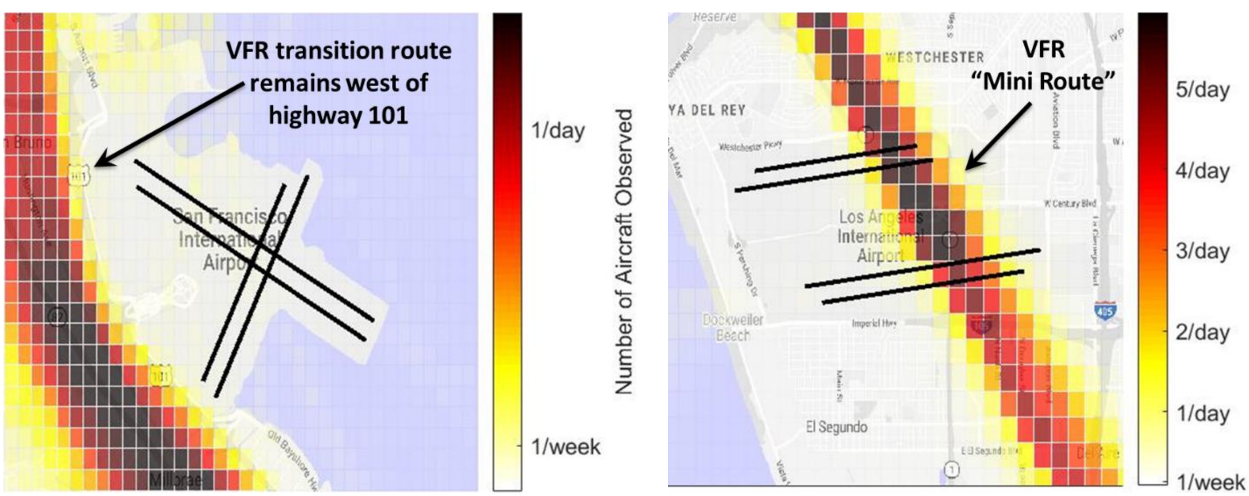
This appendix presents analysis of UAM operations that transit an airport or airport's airspace without arriving or departing from the airport.

Background on Current Operations

Small aircraft and helicopters that transit terminal airspace (but do not arrive or depart at the airport) are currently supported through a variety of ATC methods, two of which are displayed in Fig. 101. First, SFO defined a series of transition routes that allow aircraft operating under Visual Flight Rules (VFR) to follow highway 101 west of the airport. Second, LAX developed a transition route where small aircraft follow a radio beacon radial to cross perpendicular to the runways. The density of operations in Fig. 101 displays the high level of navigational accuracy that was achieved through both the visual and radio navigational techniques. However, both these transit techniques require aircraft communication with controllers contributing to their workload and liming throughput potential.

As an alternative to direct controller communication, LAX also developed a Special Flight Rules Area (SFRA) located 500 ft above the "mini" route displayed in Fig. 101. The SFRA is an airspace volume through which small aircraft may cross LAX without contacting controllers; it may be thought of as a "cutout" from the LAX controller airspace.

BOS takes a different approach to mitigate increased controller workload and radio frequency congestion from small aircraft and helicopter operations by assigning a dedicated controller position to serve these flights.



SFO Visual Transition Route (500-2000 ft AGL) *LAX Radio Beacon "Mini" Route (2000-3000 ft AGL)*

Fig. 101 Current small aircraft and helicopter transit operations near airports.

Airport Transit Topological Model

UAM aircraft may benefit from crossing the arrival or departure paths of conventional aircraft to more efficiently access the airport, or simply to transit through the airport area. The development of non-interfering crossing routes is therefore another important aspect of UAM ATC integration at airports.

UAM operations in proximity to airports that do not actually takeoff or land at the airport require different topological representations than those presented for airport arrival and departure operations. Fig. 102 displays the four UAM transit topologies considered in this study. The transit topologies are distinguished by how (or if) they interact with conventional flight operations and air traffic controllers. The primary design variables are the lateral and vertical location of the transit route with respect to the airport runways, conventional approach and departure procedures, and the controlled airspace boundaries.

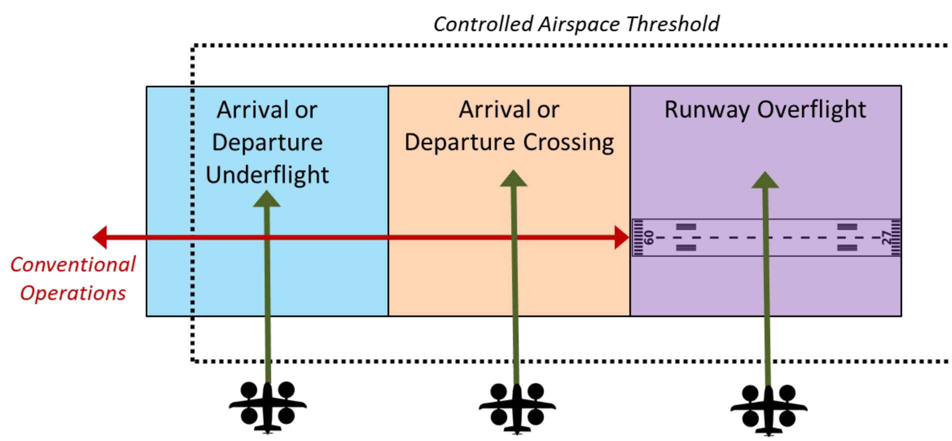


Fig. 102 Topological model of UAM ATC for airport transits.

The following sections summarize how separation minima, controller workload, and CNS equipage may constrain the development of ATC ConOps for each airport access or transit topology. This information supports the evaluation of throughput scaling for the topologies.

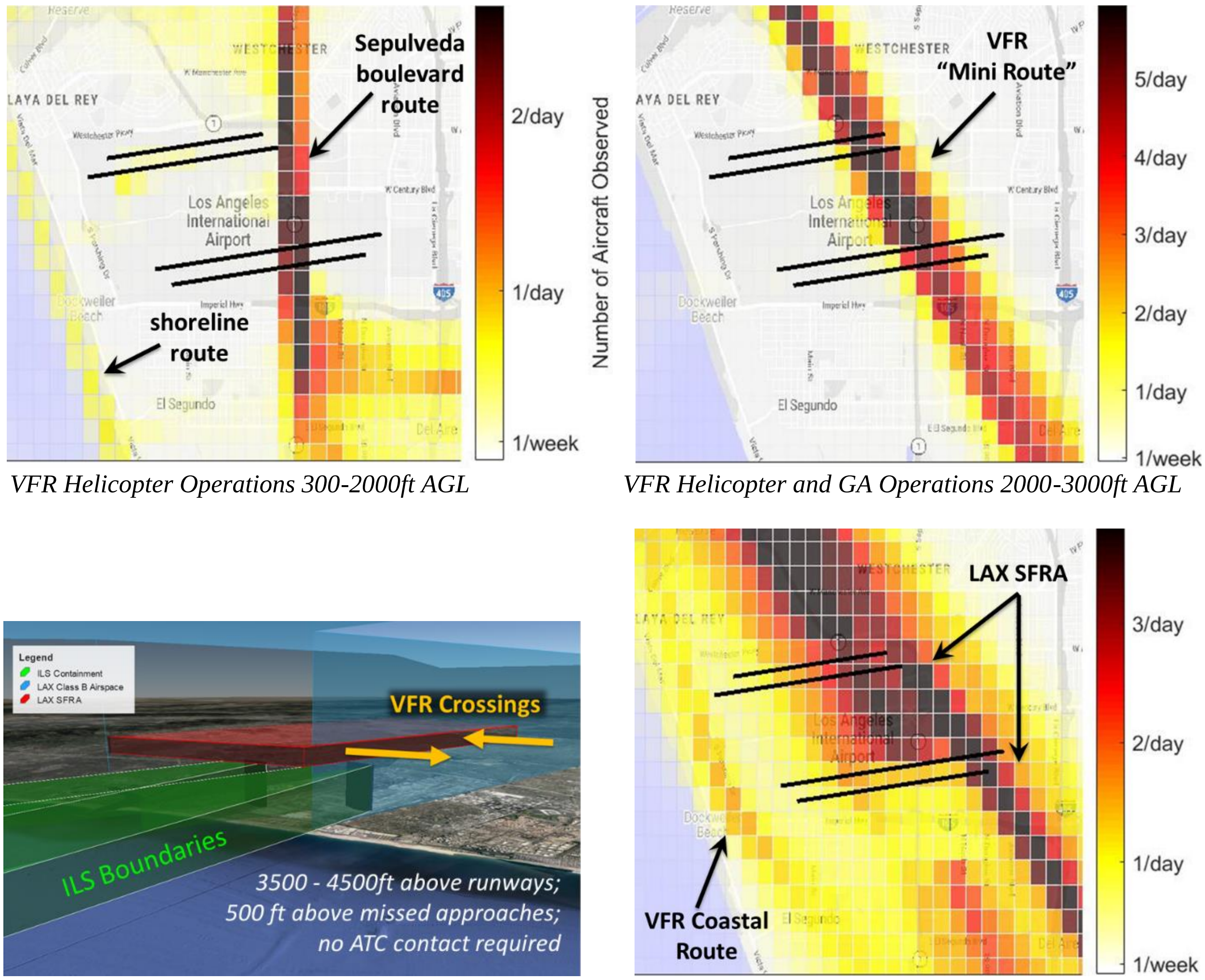
In summary, the underflight, and overflight topologies enable the greatest throughput and flexibility for UAM routing for VFR operations. For IFR operations, the runway overflight topology supports the greatest throughput in proximity to the airport, and the underflight topologies support an equivalent scale of operations at further distances from the airport. The crossing topology restricts UAM throughput and is limited by controller workload.

Runway Overflight Topology

One method of enabling airport crossings is to direct small aircraft and helicopter operations to cross perpendicularly over the active runways. Analysis of radar tracking data found this approach to commonly be used at EWR, ATL, and LAX.

Fig. 103 displays three different techniques for this transit topology all simultaneously in effect at LAX. First, the Sepulveda helicopter route allows helicopters to visually follow the Sepulveda Boulevard to cross LAX at approximately 1300 ft AGL. Of note, the majority of helicopter tracks on the Sepulveda route in Fig. 103 display a cross-track error of less than 0.1 NM.

Next, the VFR "mini" route allows aircraft and helicopters to transit LAX at 2500 ft MSL following a radio beacon vector. Although the average cross-track error is larger than for the Sepulveda route, the navigational accuracy of this VFR route remains quite high. Finally, the LAX Special Flight Rules Area (SFRA) enables aircraft or helicopter to cross LAX between 3500 ft and 5000 ft. Furthermore, as an airspace "cutout", the SFRA is the only crossing option of the three that does not require any communication with air traffic controllers.



VFR Helicopter Operations 300-2000ft AGL

VFR Helicopter and GA Operations 2000-3000ft AGL

Visualization of LAX Special Flight Rules Area (SFRA)

VFR Helicopter and GA Operations 3000-5000ft AGL

Fig. 103 LAX runway overflight transit routes for helicopters and fixed-wing aircraft.

In general, crossing routes must either provide visual separation or radar separation between aircraft on arrival or departure and transiting aircraft. Radar separation is typically assured by designing transition routes with a floor altitude that is vertically separated from the missed approach altitude or the approach procedures or the minimum vectoring altitude which a controller could assign a missed approach to maintain.

This primary limitation of this crossing topology is that low altitude transits increase controller workload and are only viable for VFR operations, and higher-altitude transits in an SFRA may be above the desired cruise altitude of the UAM aircraft. However, for UAM IFR operations this topology provides a means to use vertical radar separation to support UAM airport transits.

Arrival/Departure Underflight Topology

A second transit topology is crossing routes beneath the conventional arrivals or departures. This topology mitigates the concern of potential conflicts during missed approach or go-around procedures. However, the topology is limited in how close to the airport UAM vehicles may cross by the glidepath angle or minimum climb rate of the conventional procedures.

BOS controllers will routines clear helicopters on crossing routes 500 ft below the glideslope of arrivals to runway 04L or 04R. However, if wake turbulence is a risk factor based on the size of the arriving aircraft, then the helicopter pilots must accept the responsibility to provide their own separation visually.

Due to the impact of wake vortex separation, procedure underflight may reduce UAM throughput. Furthermore, viable UAM VFR underflight routes require a minimum of 500 ft vertical separation from the conventional aircraft while IFR routes require 1000 ft. Passenger carrying UAM operations are limited to a minimum flight altitude of 300 ft AGL. Taken together, the closest viable UAM crossing route under an arrival procedure with a standard glideslope would be 2.5 NM or 4.1 NM from the airport for VFR and IFR operations, respectively. Note that this does not provide any buffer for a low approach or above-altitude transit.

Considering the limitations imposed on underflight transits by wake vortex and vertical separation minima, this topology may limit UAM throughput unless located numerous miles from the airport.

Arrival/Departure Crossing Topology

The third transit topology considers dependent crossing routes that may be located closer to the conventional runway thresholds than underlflight routes, and at lower altitudes than the overflight routes.

Fig. 104 displays the basic geometry of a crossing route. Conventional aircraft operate on a procedure centerline surrounded by a “containment boundary” representing the potential cross-track and vertical variance of their operations. UAM aircraft operate on a crossing route that is perpendicular to the conventional flights. UAM aircraft must wait at a hold point at which they either apply visual separation to the conventional aircraft. When granted clearance to cross, UAM aircraft must cross the projected path of the conventional flight before the appropriate separation requirement is violated. This separation minima is three nautical miles in IMC and either 1.5 NM or visual separation in VMC. Furthermore, to avoid collision alerts in the conventional aircraft, the crossing must be completed while the conventional aircraft is more than 25s from the crossing route.

Analysis of radar trajectory data ascertained how precisely conventional arrivals and departures fly on the procedure centerline [137]. Fig. 105 displays the average dimensions of the containment boundary volumes for 99.5% of flights to or from the four primary BOS runways. Arrivals have a very tight containment below 2000 ft in width within three nautical miles of the airport. Departures, on the other hand, have rapid fanning of flights exceeding a containment width of 10,000 ft before two nautical miles from the threshold. UAM Crossing routes for departure procedures were not considered further as a result.

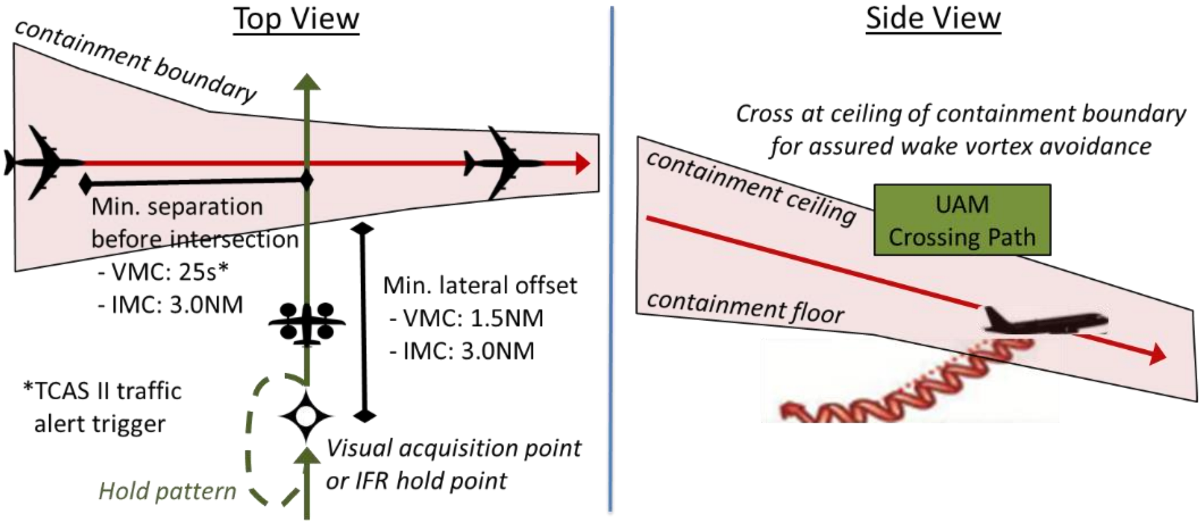


Fig. 104 Geometry of notional UAM crossing route.

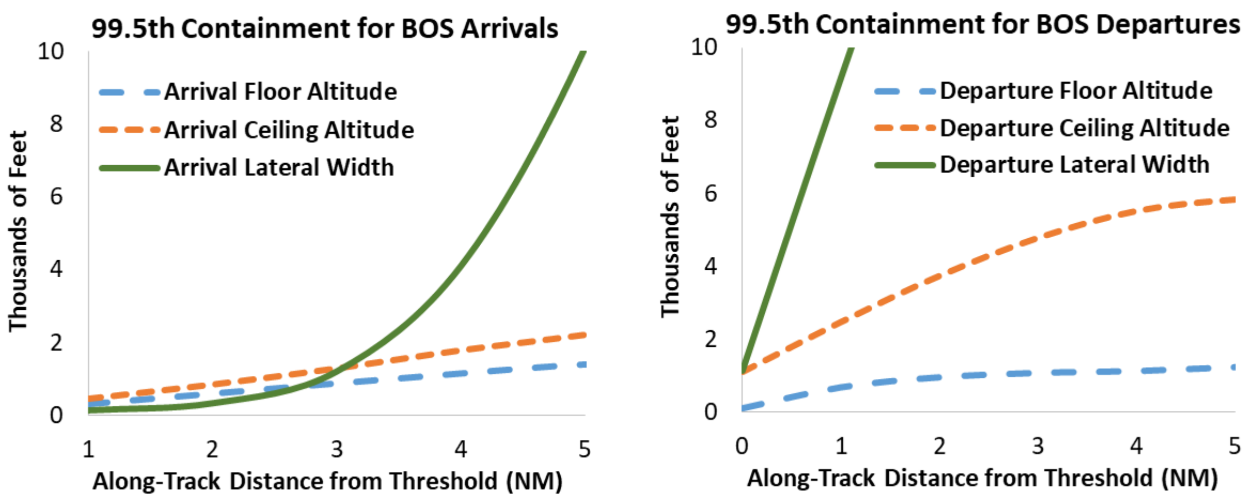


Fig. 105 Average containment boundary dimensions for 180 days of operation at Boston.

Fig. 106 presents the inter-arrival spacing between conventional aircraft that would be required to support UAM crossing operations that meet all separation requirements. The conventional aircraft velocity was assumed to be 120 kts for the IFR case, and all cases were calculated for a crossing within three nautical miles of Boston with a containment lateral width of 1200 ft based on Fig. 105. Increasing UAM crossing velocity has a greater impact when the lateral offset distance from the conventional procedure is large. However, reducing the offset distance is the most critical factor. This distance may be reduced through the use of visual separation by the pilot rather than radar separation by the controller.

With an initial lateral offset of 0.5 NM or less from the containment boundary, the required inter-arrival time is on the order of 60s which matches the typical spacing identified for arrival operations to Boston. Therefore, arrival crossing procedures close-in to an airport may be feasible for VFR UAM integration at an airport, albeit with significant sequencing required by controllers leading to increased workload. The development of controller support systems to monitor and controller UAM crossing routes similar to the arrival departure window tool [138] could increase the throughput and viability of this topology.

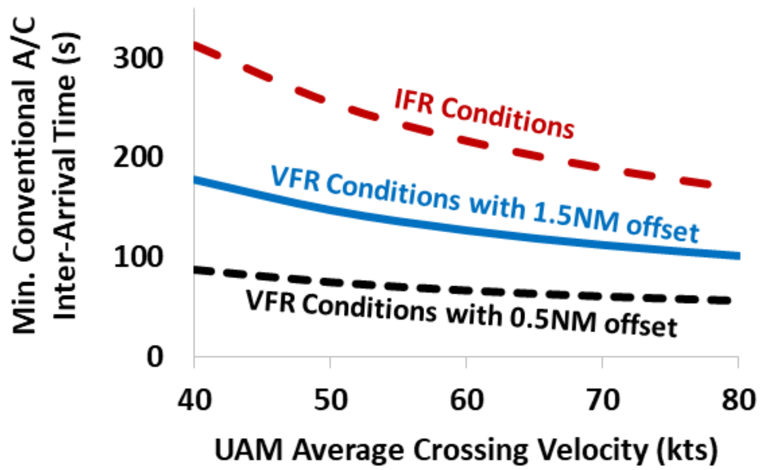


Fig. 106 Required minimum conventional aircraft inter-arrival time to enable UAM crossing of arrival procedures within three nautical miles of Boston.

Appendix C: Heat maps of helicopter and GA aircraft operations

This appendix presents investigates current helicopter and GA aircraft operations with up to 19 passenger seats in five cities. The current operations are evaluated through the use of radar tracking data obtained from Airport Surface Detection Equipment, Model X (ASDE-X). The radar data provides information on all flights that occur within approximately ten nautical miles of the airports. The position (latitude, longitude, altitude) and traffic density of the flight tracks provides an impression of how each of these UAM-like operations currently utilize airspace and airport infrastructure in these cities.

One year of radar flight tracking data spanning from April 2015 to March 2016 was collected for Boston (BOS), San Francisco (SFO), Atlanta (ATL), Newark (EWR), and Los Angeles (LAX) international airports. Of the initial data set, approximately 180 days had a full 24 hours of flight tracking records and were utilized for the analysis. ASDE-X data was selected for this analysis as it combines surface surveillance radar, multilateration sensors, airport surveillance radars, and Automatic Dependent Surveillance - Broadcast (ADS-B) data in order to provide a high-fidelity record of aircraft operations with as low as a one second update rate. ASDE-X was the best data option to capture helicopter and GA operations (which may not be equipped with an ADS-B), as well as provide sufficient resolution to represent maneuvers in terminal airspace. The flight tracks were smoothed where necessary and incomplete or infeasible trajectories were discarded.

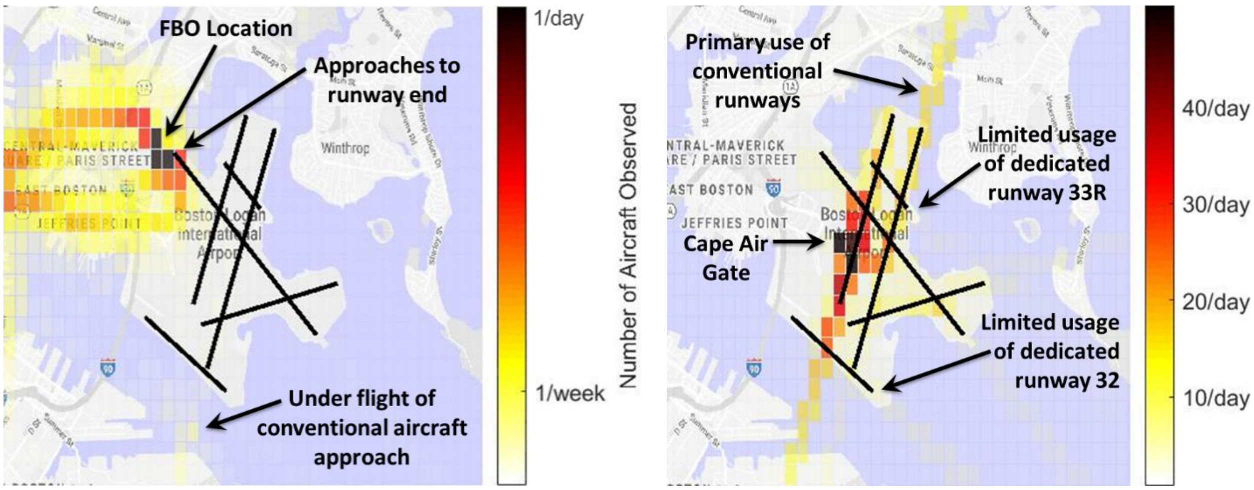
The flight tracks were sorted into the six operational categories listed below based upon the reported type of aircraft and callsign (i.e., flight number). Because GA and helicopter operators did not often report either of these data, the flight tracks for these operators were identified based upon altitude and speed characteristics.

1. large transport aircraft: >100 passengers (eg. B737, E170)
2. regional aircraft: 20-100 passengers (eg. E145, CRJ7)
3. business aircraft: (eg. GLF6, LJ70)
4. large general aviation aircraft: 6-19 passengers (eg. C402, BE80)
5. small general aviation aircraft: <5 passengers (eg. SR22, C172)
6. helicopters

Departing and arriving flights were distinguished by identifying if the initial or final data points in the flight track were located on the surface of the airport, respectively. Transiting flights were distinguished if no part of the flight track came within 100 ft AGL over any runway. The flight data was aggregated for each operator and region. Each region is discretized into evenly spaced cells, and then the results are visualized as a heat map that displays how many flight tracks were observed in each cell. Review of the heat maps reveal how the various operators currently use airspace and airport infrastructure in each region.

Boston

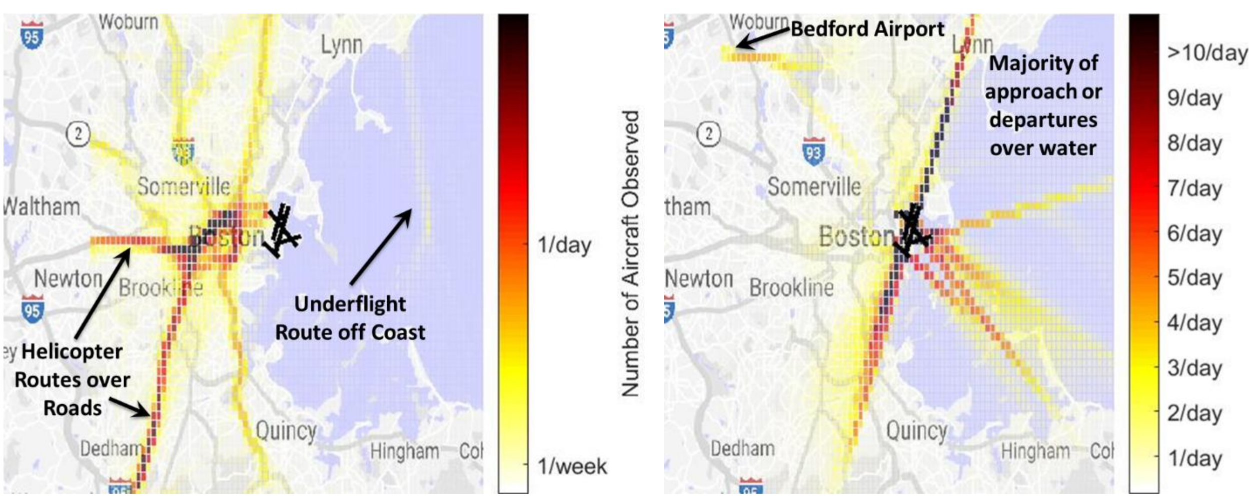
Fig. 107 displays helicopter and GA operations occurring below 1000 ft AGL at BOS. All flights in Fig. 107 were positively identified through a reported aircraft model. Key attributes of the operation include helicopter arrivals and departures on the end of runway 15R or its associated taxiway before taxiing into the FBO. GA operations at BOS were more numerous than any other airport largely due to Cape Air, a part 135 commuter airline who services operations directly to a gate at Terminal C. The GA operations shared the conventional runway, and had limited use of two short length runways.



Positively identified helicopter operations *Positively identified GA operations*

Fig. 107 Helicopter and GA arrivals and departures to Boston airport.

Fig. 108 displays helicopter and GA operations below 2500 ft AGL (measured from the airport's altitude) throughout the broader Boston metropolitan area. The terminal airspace for BOS has defined helicopter routes that primarily follow the highways in the region and support the large majority of helicopter operations. GA arrivals and departures to BOS occur primarily over water.



Positively identified helicopter operations *Positively identified GA operations*

Fig. 108 Helicopter and GA operations below 2500 ft AGL in the Boston area.

Fig. 109 displays a heat map of large transport and regional aircraft operations below 2500 ft AGL in the Boston area. These large aircraft operate exclusively on approach and departure procedures to and from Logan airport, respectively.

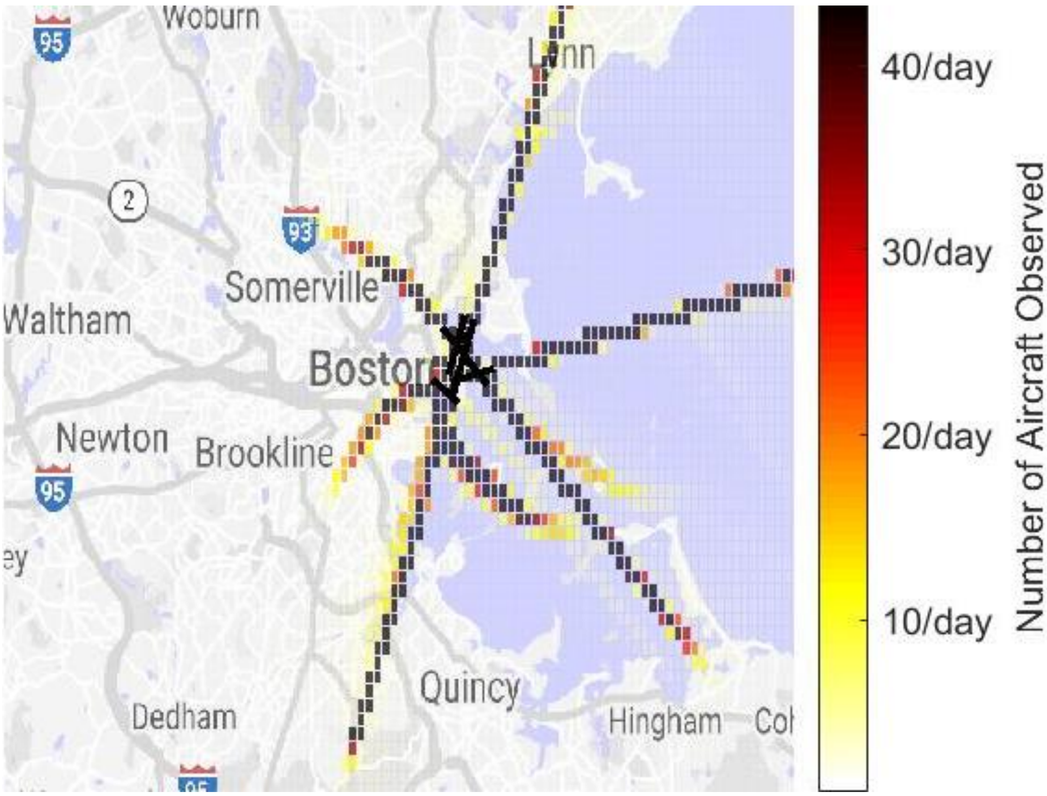


Fig. 109 Frequency of large transport and regional aircraft operations below 2500 ft AGL in Boston. Max cell density is 270 flights per day.

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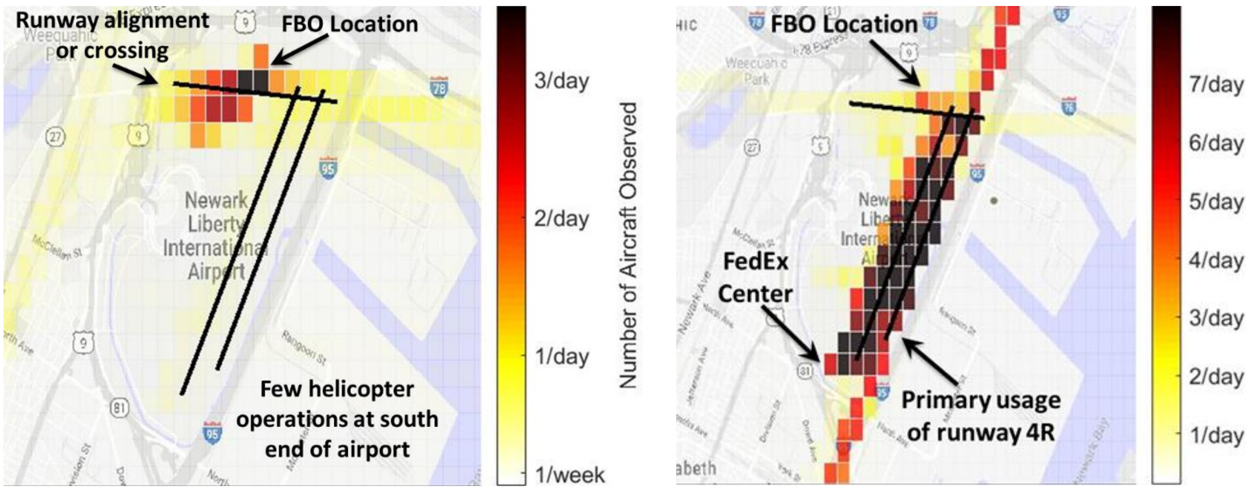
Newark

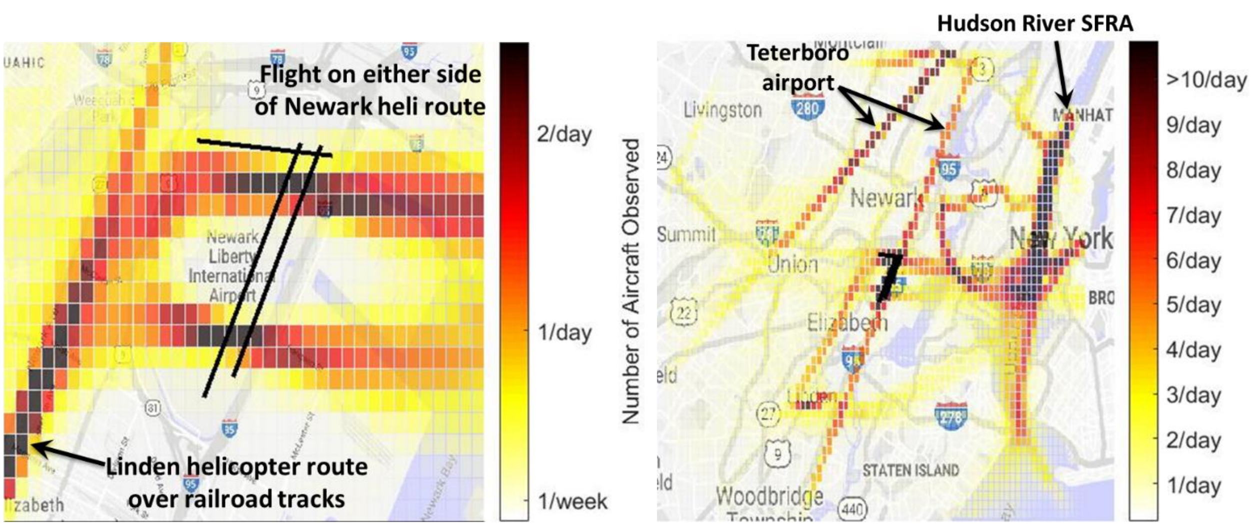
Fig. 110 displays helicopter and GA operations occurring below 1000 ft AGL at EWR. Helicopter operations primarily land or depart on runway 11 and its associated taxiway before taxiing to the FBO location. Small GA operations (<5 PAX) primarily use runway 4R and taxi to the FBO, however larger GA operations are dominated by the FedEx air shipment center located at the south end of the airport.



Positively identified & inferred helicopter operations *Positively identified & inferred GA operations*

Fig. 110 Helicopter and GA arrivals and departures to Newark airport.

Fig. 111 first shows helicopter operations between 500 ft and 2000 ft AGL around EWR. A majority of flights operate on the Linden helicopter route west of the airport which visually follows a railroad. Interestingly, flights that transit over EWR operate on either side of the defined helicopter route. This may be the result of established bi-directional travel patterns that are laterally offset on from the helicopter route centerline. Fig. 111 also displays helicopter and GA flights in the broader New Jersey and New York region. The highest density paths are GA arrivals and departures to Teterboro airport, helicopter flights connecting EWR and a heliport to Manhattan, and the Hudson River SFRA. The SFRA is a unique feature of New York that enables GA aircraft or helicopters to operate without requiring contact with ATC.

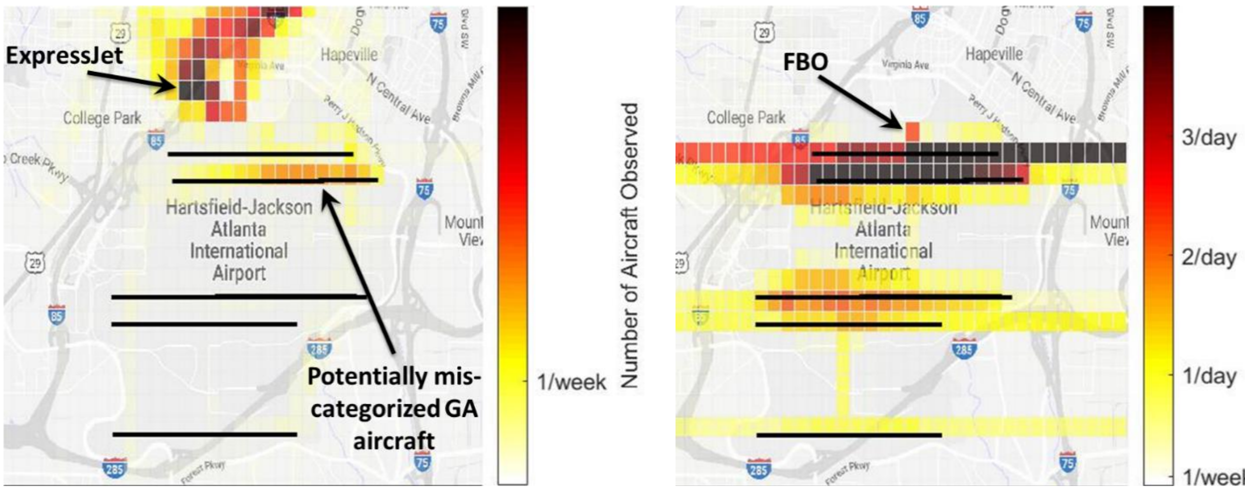


Positively identified & inferred helicopter transits *Helicopter and GA operations below 2500 ft AGL*

Fig. 111 Transiting operations over Newark airport and all operations in the New Jersey area.

Atlanta

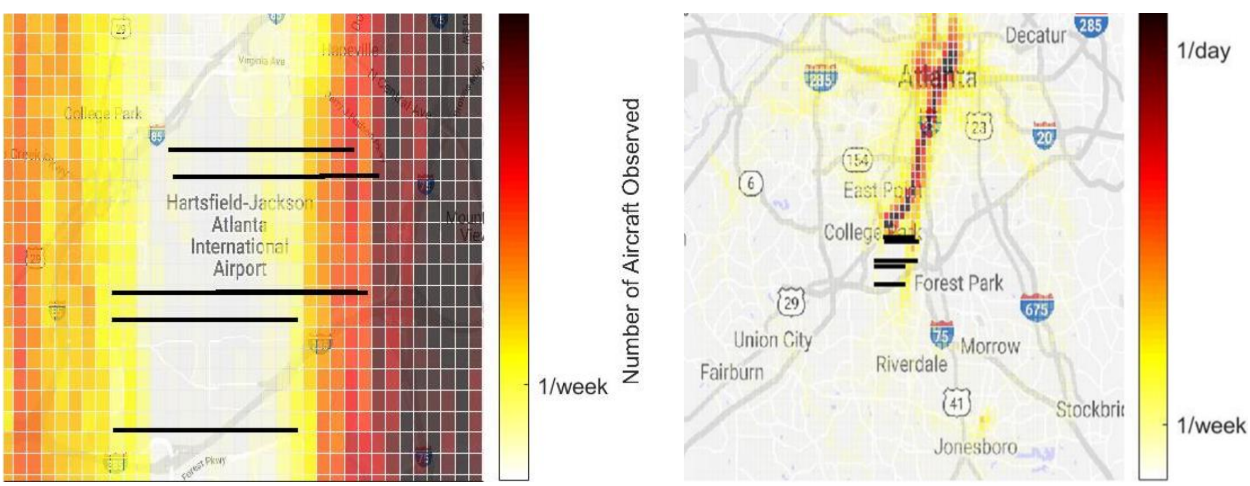
Fig. 112 displays helicopter and GA operations occurring below 1000 ft AGL at ATL. Nearly all identified helicopter operations to ATL directly approached and departed from the ExpressJet hangar to the north of the airport. While some helicopter operations may have landed on 26R or 26L and taxied to the FBO location, the concentration of flights on 26L is believed to be miss-categorized GA operations rather than helicopter flights. GA operations primarily landed on 26L or 26R before proceeding to the FBO.



Positively identified & inferred helicopter operations *Positively identified & inferred GA operations*

Fig. 112 Helicopter and GA arrivals and departures to Atlanta airport.

Fig. 113 first displays the airport transit topology for GA operations at ATL. GA flights travel perpendicularly to the runways between the altitudes of 2000 ft and 5000 ft AGL. The second sub-figure in Fig. 113 displays helicopter operations below 2500 ft AGL in the Atlanta metropolitan area. The primary corridor of travel appears to be between the airport and the city center as well as around the downtown area. The density of these flights is low, however, compared to the other cities of the study. No definitive conclusion is possible as the low percentage of aircraft type reporting in the ASDE-X data may have led to an under-identification of helicopter flights.

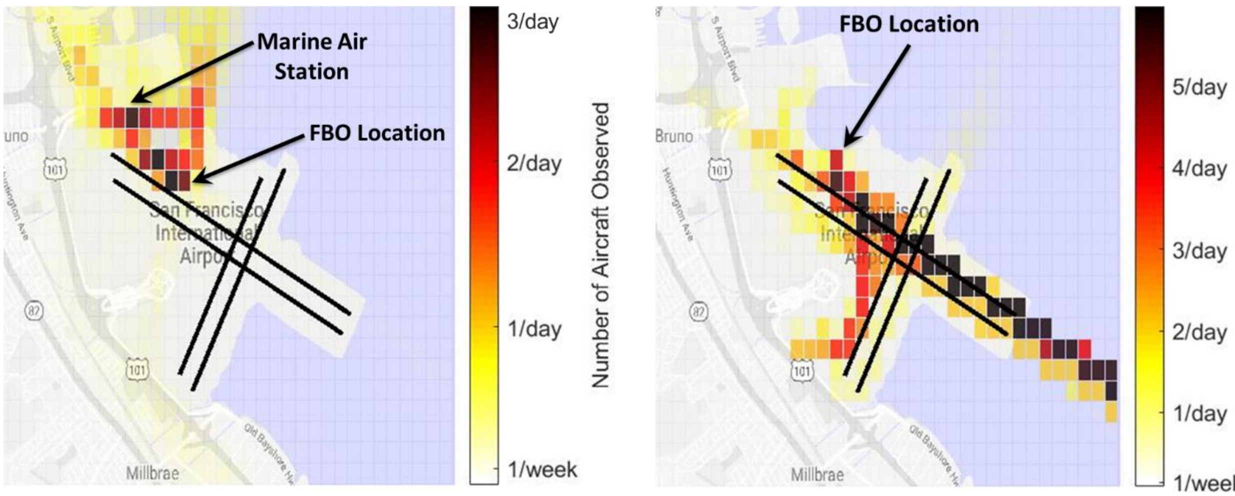


Positively identified & inferred GA transits *Helicopter operations below 2500ft AGL*

Fig. 113 Helicopter and GA operations below 2500 ft AGL in the Newark area.

San Francisco

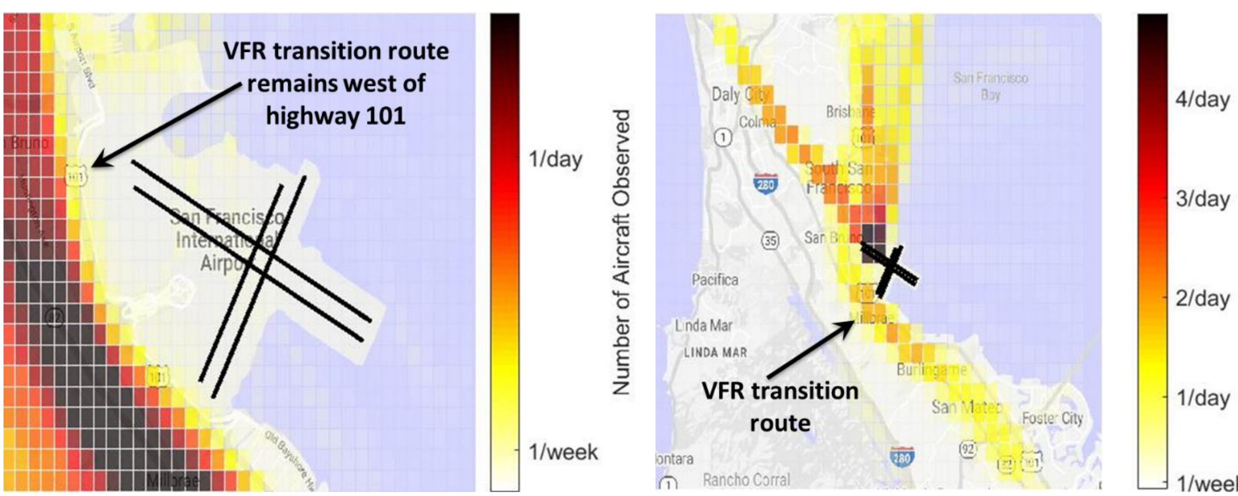
Fig. 114 displays helicopter and GA operations occurring below 1000 ft AGL at SFO. Similar to Boston and Atlanta, helicopters at SFO approach in a manner that does not overfly a runway or interfere with the conventional traffic pattern. There are two major landing areas for helicopters at SFO; one helipad is located at the FBO and the other is at the Marine Air Station. GA operations tend to use runway 28R before taxiing to either the FBO or terminal B.



Positively identified & inferred helicopter operations *Positively identified & inferred GA operations*

Fig. 114 Helicopter and GA arrivals and departures to San Francisco airport.

Fig. 115 displays the transit route topology for helicopters and GA aircraft at SFO. Due to the infrequent use of departures on 28L/R or 19L/R, small aircraft can typically use a VFR route located immediately west of the airport to transition the SFO terminal area. Pilots are requested to remain west of highway 101, and the heat map in Fig. 115 displays high adherence to this rule. The second sub-figure in Fig. 115 displays helicopter operation in the broader San Francisco region. The operations pass north of the airport following highway 101 and then pass either east or west of the San Bruno Mountain to travel up to the primary city center (not shown).

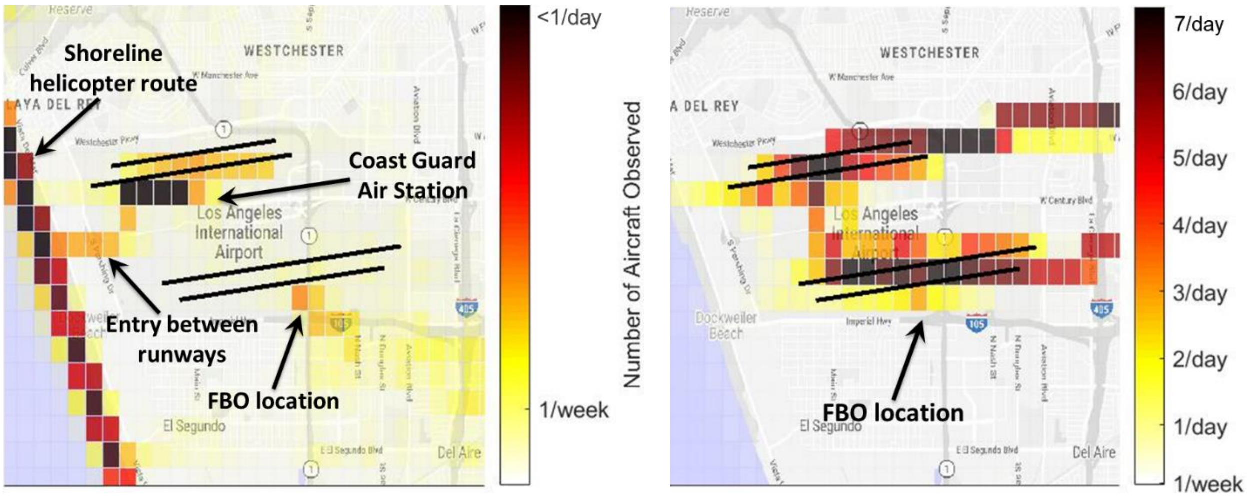


GE and helicopter transits of SFO 500-2000 ft AGL *Helicopter operations below 2500 ft AGL*

Fig. 115 Helicopter and GA operations in the San Francisco Bay Area.

Los Angeles

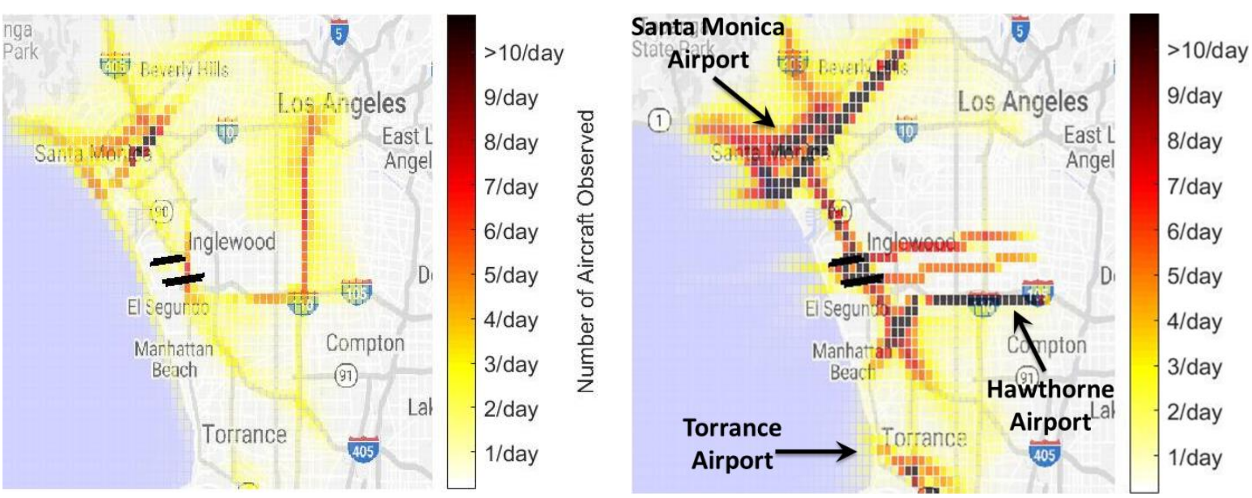
Fig. 116 displays helicopter and GA operations below 1000 ft AGL at LAX. Unlike all other airports in this study, LAX was the only airport where helicopters approached a landing area located between parallel runways. This was done by flying in front of the runway thresholds on a helicopter route before turning into the airport between the runways. A separate stream of helicopter operations was identified directly at the FBO similar to flights at BOS, ATL, and SFO.



Positively identified & inferred helicopter operations   *Positively identified & inferred GA operations*

Fig. 116 Helicopter and GA arrivals and departures to Los Angeles airport.

Fig. 117 displays helicopter and GA operations below 2500 ft AGL in the Los Angeles region. Los Angeles had a significantly higher number of GA operations than any other city in this study, as well as roughly as many helicopter operations as in the Newark region. Furthermore, due to numerous active GA airports in the Los Angeles basin, GA operations were distributed among many locations rather than concentrated in one area. Helicopter operations were also distributed throughout the LA and a helicopter route network follows the freeways and shoreline.



Positively identified & inferred helicopter operations   *Positively identified & inferred GA operations*

Fig. 117 Helicopter and GA operations below 2500 ft AGL in the Los Angeles region.

Appendix D: Additional Results of UAM Scaling Analysis in 34 U.S. Metropolitan Areas

This appendix contains additional results from the analysis of UAM scaling potential in the 34 largest U.S. Metropolitan Statistical Areas (MSAs). Chapter 9 discusses the approach and assumptions of the analysis. Findings are also discussed in Chapter 9.

Three types of additional results are presented in this appendix. First, tables presenting the mission coverage for each of the four demands types considered for UAM are provided. Second, select images of UAM mission coverage are provided for additional MSAs. Third, an analysis of UAM interoperability at the 49 large commercial airports in the MSAs is provided.

Mission Coverage in 34 MSAs for Four UAM Mission Coverage Metrics

Table 32 through Table 35 summarize the UAM mission coverage by percentage for the four types of UAM demand considered in this thesis. Entries of "N/A" indicate cases where no census tracts supported 500 or more existing long-duration commuters. Table 36 through Table 39 present mission coverage based on the total population (for the air taxi mission) or the total number of long-duration commuters (for the commuter mission) that may be accessed in each MSA without ATC interaction.

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Table 32. Percentage of the total population accessible to UAM in five ATC ConOps scenarios.

	Population Coverage by ATC ConOps Scenario:				
Metropolitan Area	*Fully segregated from SUA and terminal airspace*	*Access to SUA*	*Access to airspace at low-traffic airports*	*Access to static VFR cutouts*	*Access to SUA, low-traffic airspace, & static VFR cutout*
Indianapolis, IN	85%	89%	88%	87%	97%
Charlotte, NC	81%	84%	83%	88%	98%
Sacramento, CA	79%	79%	79%	89%	89%
Pittsburgh, PA	77%	85%	87%	80%	99%
Austin, TX	77%	85%	81%	84%	96%
Cincinnati, OH	76%	84%	76%	83%	93%
Kansas City, MO	76%	80%	84%	83%	97%
Tampa, FL	75%	75%	75%	87%	88%
St. Louis, MO	75%	78%	76%	87%	93%
Detroit, MI	74%	75%	82%	85%	96%
Atlanta, GA	72%	77%	77%	84%	94%
Cleveland, OH	70%	71%	83%	77%	95%
Portland, OR	70%	70%	70%	87%	88%
Philadelphia, PA	67%	70%	81%	79%	97%
Orlando, FL	67%	74%	69%	72%	85%
Chicago, IL	66%	77%	70%	77%	92%
Riverside, CA	66%	69%	66%	84%	87%
Denver, CO	64%	76%	64%	82%	93%
Baltimore, MD	64%	75%	64%	80%	94%
Houston, TX	62%	65%	70%	80%	94%
Boston, MA	61%	63%	74%	72%	93%
Columbus, OH	60%	66%	67%	75%	91%
Minneapolis, MN	59%	65%	59%	69%	94%
Phoenix, AZ	59%	62%	59%	80%	88%
Seattle, WA	58%	66%	61%	75%	87%
Dallas, TX	56%	60%	64%	73%	90%
New York City, NY	55%	57%	56%	76%	87%
San Antonio, TX	54%	56%	56%	80%	83%
San Diego, CA	53%	54%	53%	69%	77%
San Francisco, CA	48%	64%	48%	65%	86%
Los Angeles, CA	44%	54%	44%	67%	79%
Miami, FL	43%	44%	43%	67%	73%
Washington, DC	34%	57%	34%	44%	90%
Las Vegas, NV	24%	24%	25%	71%	76%

Table 33. Percentage of the long-duration commuter workplaces accessible to UAM in five ATC ConOps scenarios.

	Long-Duration Commuter Workplace Coverage by ATC ConOps Scenario:				
Metropolitan Area	*Fully segregated from SUA and terminal airspace*	*Access to SUA*	*Access to airspace at low-traffic airports*	*Access to static VFR cutouts*	*Access to SUA, low-traffic airspace, & static VFR cutout*
Indianapolis, IN	81%	86%	81%	84%	92%
Portland, OR	68%	68%	68%	85%	85%
San Antonio, TX	65%	65%	65%	83%	83%
Detroit, MI	64%	83%	66%	65%	93%
Philadelphia, PA	60%	84%	67%	60%	94%
Sacramento, CA	54%	54%	54%	90%	90%
Houston, TX	48%	61%	52%	56%	93%
Cincinnati, OH	46%	93%	46%	47%	98%
New York City, NY	40%	41%	40%	83%	90%
Kansas City, MO	38%	38%	38%	44%	44%
Austin, TX	38%	90%	38%	45%	98%
Baltimore, MD	38%	78%	38%	51%	96%
Tampa, FL	37%	43%	37%	40%	45%
Atlanta, GA	37%	68%	38%	54%	88%
Riverside, CA	35%	38%	35%	53%	60%
Seattle, WA	35%	60%	35%	40%	81%
St. Louis, MO	35%	55%	35%	46%	80%
Orlando, FL	33%	48%	35%	35%	58%
Los Angeles, CA	31%	47%	31%	56%	73%
San Diego, CA	30%	32%	30%	39%	48%
Charlotte, NC	30%	30%	32%	49%	84%
Phoenix, AZ	26%	31%	26%	35%	53%
Cleveland, OH	25%	25%	45%	25%	100%
San Francisco, CA	24%	77%	24%	32%	86%
Chicago, IL	24%	78%	24%	31%	87%
Denver, CO	22%	70%	22%	33%	82%
Minneapolis, MN	21%	63%	21%	31%	92%
Dallas, TX	19%	23%	20%	44%	70%
Miami, FL	18%	23%	18%	36%	68%
Columbus, OH	15%	45%	20%	30%	74%
Boston, MA	15%	18%	19%	23%	49%
Pittsburgh, PA	10%	100%	10%	10%	100%
Washington, DC	6%	26%	6%	12%	66%
Las Vegas, NV	0%	0%	0%	18%	22%

Table 34. Percentage of the current long-duration commuter residences accessible to UAM in five ATC ConOps scenarios.

Metropolitan Area	Current Long-Duration Commuter Residence Coverage by ATC ConOps Scenario:				
	Fully segregated from SUA and terminal airspace	*Access to SUA*	*Access to airspace at low-traffic airports*	*Access to static VFR cutouts*	*Access to SUA, low-traffic airspace, & static VFR cutout*
Cincinnati, OH	100%	100%	100%	100%	100%
Columbus, OH	100%	100%	100%	100%	100%
Kansas City, MO	100%	100%	100%	100%	100%
Pittsburgh, PA	100%	100%	100%	100%	100%
Sacramento, CA	100%	100%	100%	100%	100%
St. Louis, MO	100%	100%	100%	100%	100%
Minneapolis, MN	100%	100%	100%	100%	100%
San Antonio, TX	100%	100%	100%	100%	100%
Detroit, MI	99%	99%	99%	100%	100%
Indianapolis, IN	93%	93%	93%	100%	100%
Orlando, FL	89%	90%	89%	91%	96%
Portland, OR	89%	89%	89%	100%	100%
Austin, TX	89%	89%	93%	98%	100%
San Diego, CA	88%	88%	88%	88%	88%
Phoenix, AZ	85%	88%	85%	93%	96%
Tampa, FL	85%	85%	85%	97%	97%
Atlanta, GA	83%	83%	88%	92%	98%
Baltimore, MD	82%	86%	82%	95%	99%
Chicago, IL	82%	90%	82%	87%	96%
Dallas, TX	77%	77%	83%	84%	91%
Seattle, WA	76%	76%	76%	92%	92%
Denver, CO	73%	85%	73%	88%	100%
Houston, TX	71%	71%	80%	85%	94%
Boston, MA	71%	72%	78%	85%	94%
San Francisco, CA	71%	78%	71%	86%	93%
Riverside, CA	71%	75%	71%	87%	92%
Washington, DC	58%	72%	58%	72%	93%
Philadelphia, PA	58%	62%	86%	66%	98%
Los Angeles, CA	54%	61%	54%	79%	86%
New York City, NY	49%	50%	49%	72%	84%
Miami, FL	36%	36%	36%	64%	70%
Charlotte, NC	N/A	N/A	N/A	N/A	N/A
Cleveland, OH	N/A	N/A	N/A	N/A	N/A
Las Vegas, NV	N/A	N/A	N/A	N/A	N/A

Table 35. Percentage of the induced commuter residences accessible to UAM in five ATC ConOps scenarios.

	Induced Long-Duration Commuter Residence Coverage by ATC ConOps Scenario:				
Metropolitan Area	*Fully segregated from SUA and terminal airspace*	*Access to SUA*	*Access to airspace at low-traffic airports*	*Access to static VFR cutouts*	*Access to SUA, low-traffic airspace, & static VFR cutout*
Cleveland, OH	100%	100%	100%	100%	100%
Kansas City, MO	100%	100%	100%	100%	100%
Charlotte, NC	97%	98%	98%	97%	100%
Indianapolis, IN	95%	95%	95%	98%	98%
Sacramento, CA	94%	94%	94%	97%	97%
Cincinnati, OH	93%	95%	93%	98%	99%
Minneapolis, MN	92%	93%	92%	94%	100%
Columbus, OH	91%	91%	93%	97%	99%
St. Louis, MO	91%	91%	92%	96%	99%
Tampa, FL	89%	89%	89%	96%	96%
Austin, TX	88%	88%	94%	93%	98%
Pittsburgh, PA	85%	85%	97%	86%	99%
Detroit, MI	82%	82%	83%	92%	93%
Atlanta, GA	81%	81%	84%	91%	95%
Portland, OR	75%	76%	75%	90%	91%
Dallas, TX	75%	77%	85%	82%	96%
Baltimore, MD	74%	81%	74%	87%	95%
San Antonio, TX	74%	76%	80%	81%	89%
Denver, CO	72%	75%	72%	91%	93%
Seattle, WA	69%	70%	71%	86%	89%
Chicago, IL	68%	78%	70%	80%	91%
Orlando, FL	67%	78%	67%	73%	89%
Phoenix, AZ	66%	73%	66%	83%	90%
Philadelphia, PA	66%	69%	83%	75%	97%
Riverside, CA	65%	67%	65%	85%	87%
Houston, TX	64%	65%	72%	84%	93%
Boston, MA	62%	64%	75%	75%	95%
San Diego, CA	61%	61%	61%	76%	82%
New York City, NY	55%	57%	56%	78%	87%
Miami, FL	47%	48%	47%	71%	76%
San Francisco, CA	46%	64%	46%	65%	88%
Los Angeles, CA	44%	55%	44%	66%	79%
Washington, DC	37%	61%	37%	47%	91%
Las Vegas, NV	21%	22%	21%	68%	72%

Table 36. Total population accessible by UAM in five ATC ConOps scenarios.

Metropolitan Area	Population Coverage by ATC ConOps Scenario: Fully segregated from SUA and terminal airspace	Access to SUA	Access to airspace at low-traffic airports	Access to static VFR cutouts	Access to SUA, low-traffic airspace, & static VFR cutout
New York City, NY	1.1E+07	1.1E+07	1.1E+07	1.5E+07	1.7E+07
Chicago, IL	6.2E+06	7.3E+06	6.6E+06	7.2E+06	8.7E+06
Los Angeles, CA	5.6E+06	6.9E+06	5.6E+06	8.5E+06	1.0E+07
Boston, MA	4.8E+06	4.9E+06	5.8E+06	5.6E+06	7.3E+06
Philadelphia, PA	4.0E+06	4.2E+06	4.8E+06	4.7E+06	5.8E+06
Atlanta, GA	3.8E+06	4.0E+06	4.0E+06	4.4E+06	4.9E+06
Houston, TX	3.6E+06	3.8E+06	4.1E+06	4.7E+06	5.5E+06
Dallas, TX	3.6E+06	3.8E+06	4.1E+06	4.7E+06	5.7E+06
Detroit, MI	3.1E+06	3.2E+06	3.5E+06	3.6E+06	4.1E+06
Riverside, CA	2.8E+06	2.9E+06	2.8E+06	3.5E+06	3.7E+06
Phoenix, AZ	2.4E+06	2.6E+06	2.4E+06	3.3E+06	3.6E+06
Miami, FL	2.3E+06	2.4E+06	2.3E+06	3.7E+06	4.0E+06
St. Louis, MO	2.1E+06	2.2E+06	2.1E+06	2.4E+06	2.6E+06
San Francisco, CA	2.1E+06	2.8E+06	2.1E+06	2.8E+06	3.7E+06
Tampa, FL	2.0E+06	2.1E+06	2.0E+06	2.4E+06	2.4E+06
Seattle, WA	2.0E+06	2.2E+06	2.1E+06	2.6E+06	3.0E+06
Minneapolis, MN	2.0E+06	2.2E+06	2.0E+06	2.3E+06	3.1E+06
Washington, DC	1.9E+06	3.2E+06	1.9E+06	2.5E+06	5.1E+06
Pittsburgh, PA	1.8E+06	2.0E+06	2.0E+06	1.9E+06	2.3E+06
Charlotte, NC	1.8E+06	1.8E+06	1.8E+06	1.9E+06	2.1E+06
Baltimore, MD	1.7E+06	2.0E+06	1.7E+06	2.2E+06	2.5E+06
Sacramento, CA	1.7E+06	1.7E+06	1.7E+06	1.9E+06	1.9E+06
Denver, CO	1.6E+06	1.9E+06	1.6E+06	2.1E+06	2.4E+06
San Diego, CA	1.6E+06	1.7E+06	1.6E+06	2.1E+06	2.4E+06
Cincinnati, OH	1.6E+06	1.8E+06	1.6E+06	1.7E+06	2.0E+06
Indianapolis, IN	1.6E+06	1.7E+06	1.6E+06	1.6E+06	1.8E+06
Portland, OR	1.6E+06	1.6E+06	1.6E+06	1.9E+06	1.9E+06
Kansas City, MO	1.5E+06	1.6E+06	1.7E+06	1.7E+06	1.9E+06
Cleveland, OH	1.5E+06	1.5E+06	1.7E+06	1.6E+06	2.0E+06
Orlando, FL	1.4E+06	1.5E+06	1.4E+06	1.5E+06	1.8E+06
Austin, TX	1.3E+06	1.4E+06	1.4E+06	1.4E+06	1.6E+06
San Antonio, TX	1.2E+06	1.2E+06	1.2E+06	1.7E+06	1.8E+06
Columbus, OH	1.1E+06	1.2E+06	1.3E+06	1.4E+06	1.7E+06
Las Vegas, NV	4.7E+05	4.7E+05	4.7E+05	1.4E+06	1.5E+06

Table 37. Long-duration commuter workplaces accessible by UAM in five ATC ConOps scenarios.

Metropolitan Area	Long-Duration Commuter Workplace Coverage by ATC ConOps Scenario: Fully segregated from SUA and terminal airspace	Access to SUA	Access to airspace at low-traffic airports	Access to static VFR cutouts	Access to SUA, low-traffic airspace, & static VFR cutout
New York City, NY	5.2E+05	5.4E+05	5.2E+05	1.1E+06	1.2E+06
Los Angeles, CA	1.4E+05	2.2E+05	1.4E+05	2.7E+05	3.4E+05
Houston, TX	7.9E+04	1.0E+05	8.4E+04	9.1E+04	1.5E+05
Chicago, IL	7.6E+04	2.5E+05	7.7E+04	9.9E+04	2.8E+05
Atlanta, GA	6.1E+04	1.1E+05	6.3E+04	9.0E+04	1.5E+05
Philadelphia, PA	5.9E+04	8.3E+04	6.7E+04	6.0E+04	9.4E+04
San Francisco, CA	5.5E+04	1.8E+05	5.5E+04	7.5E+04	2.0E+05
Seattle, WA	4.7E+04	8.1E+04	4.7E+04	5.3E+04	1.1E+05
Boston, MA	3.7E+04	4.3E+04	4.6E+04	5.6E+04	1.2E+05
Detroit, MI	2.8E+04	3.6E+04	2.8E+04	2.8E+04	4.0E+04
Baltimore, MD	2.5E+04	5.1E+04	2.5E+04	3.4E+04	6.3E+04
Dallas, TX	2.3E+04	2.8E+04	2.5E+04	5.6E+04	8.8E+04
Washington, DC	2.3E+04	1.0E+05	2.3E+04	4.8E+04	2.6E+05
Portland, OR	2.1E+04	2.1E+04	2.1E+04	2.7E+04	2.7E+04
Miami, FL	1.9E+04	2.4E+04	1.9E+04	3.8E+04	7.2E+04
Riverside, CA	1.6E+04	1.7E+04	1.6E+04	2.4E+04	2.7E+04
San Diego, CA	1.5E+04	1.6E+04	1.5E+04	2.0E+04	2.4E+04
Indianapolis, IN	1.3E+04	1.4E+04	1.3E+04	1.3E+04	1.5E+04
Orlando, FL	1.2E+04	1.7E+04	1.2E+04	1.2E+04	2.0E+04
Tampa, FL	1.1E+04	1.3E+04	1.1E+04	1.2E+04	1.4E+04
Sacramento, CA	1.1E+04	1.1E+04	1.1E+04	1.8E+04	1.8E+04
Austin, TX	9.2E+03	2.2E+04	9.2E+03	1.1E+04	2.4E+04
Phoenix, AZ	9.0E+03	1.1E+04	9.0E+03	1.2E+04	1.9E+04
St. Louis, MO	8.7E+03	1.4E+04	8.7E+03	1.2E+04	2.0E+04
Denver, CO	8.4E+03	2.7E+04	8.4E+03	1.3E+04	3.2E+04
San Antonio, TX	8.4E+03	8.4E+03	8.4E+03	1.1E+04	1.1E+04
Charlotte, NC	7.2E+03	7.2E+03	7.5E+03	1.2E+04	2.0E+04
Minneapolis, MN	6.6E+03	2.0E+04	6.6E+03	9.8E+03	2.9E+04
Cincinnati, OH	5.6E+03	1.1E+04	5.6E+03	5.7E+03	1.2E+04
Cleveland, OH	4.3E+03	4.3E+03	7.6E+03	4.3E+03	1.7E+04
Kansas City, MO	2.6E+03	2.6E+03	2.6E+03	3.0E+03	3.0E+03
Pittsburgh, PA	2.5E+03	2.6E+04	2.5E+03	2.5E+03	2.6E+04
Columbus, OH	2.2E+03	6.4E+03	2.8E+03	4.2E+03	1.0E+04
Las Vegas, NV	2.7E+01	2.7E+01	2.7E+01	2.4E+03	3.0E+03

Table 38. Current long-duration commuter residences accessible by UAM in five ATC ConOps scenarios.

	Current Long-Duration Commuter Residence Coverage by ATC ConOps Scenario:				
Metropolitan Area	*Fully segregated from SUA and terminal airspace*	*Access to SUA*	*Access to airspace at low-traffic airports*	*Access to static VFR cutouts*	*Access to SUA, low-traffic airspace, & static VFR cutout*
New York City, NY	4.7E+05	4.9E+05	4.8E+05	7.0E+05	8.2E+05
Washington, DC	1.6E+05	1.9E+05	1.6E+05	1.9E+05	2.5E+05
Chicago, IL	1.2E+05	1.3E+05	1.2E+05	1.2E+05	1.4E+05
Atlanta, GA	1.1E+05	1.1E+05	1.2E+05	1.2E+05	1.3E+05
Houston, TX	1.1E+05	1.1E+05	1.2E+05	1.3E+05	1.4E+05
Riverside, CA	9.3E+04	9.8E+04	9.3E+04	1.1E+05	1.2E+05
Boston, MA	9.3E+04	9.4E+04	1.0E+05	1.1E+05	1.2E+05
San Francisco, CA	8.2E+04	9.1E+04	8.2E+04	1.0E+05	1.1E+05
Los Angeles, CA	5.1E+04	5.7E+04	5.1E+04	7.4E+04	8.0E+04
Dallas, TX	4.6E+04	4.6E+04	5.0E+04	5.0E+04	5.4E+04
Baltimore, MD	2.9E+04	3.0E+04	2.9E+04	3.4E+04	3.5E+04
Seattle, WA	2.6E+04	2.6E+04	2.6E+04	3.2E+04	3.2E+04
Philadelphia, PA	2.0E+04	2.2E+04	3.0E+04	2.3E+04	3.4E+04
Miami, FL	2.0E+04	2.0E+04	2.0E+04	3.6E+04	4.0E+04
Minneapolis, MN	1.5E+04	1.5E+04	1.5E+04	1.5E+04	1.5E+04
Austin, TX	1.5E+04	1.5E+04	1.6E+04	1.6E+04	1.7E+04
Orlando, FL	1.4E+04	1.4E+04	1.4E+04	1.4E+04	1.5E+04
Phoenix, AZ	8.9E+03	9.2E+03	8.9E+03	9.8E+03	1.0E+04
St. Louis, MO	6.7E+03	6.7E+03	6.7E+03	6.7E+03	6.7E+03
San Diego, CA	5.8E+03	5.8E+03	5.8E+03	5.8E+03	5.8E+03
San Antonio, TX	4.4E+03	4.4E+03	4.4E+03	4.4E+03	4.4E+03
Indianapolis, IN	3.9E+03	3.9E+03	3.9E+03	4.2E+03	4.2E+03
Cincinnati, OH	3.5E+03	3.5E+03	3.5E+03	3.5E+03	3.5E+03
Denver, CO	3.4E+03	4.0E+03	3.4E+03	4.1E+03	4.7E+03
Tampa, FL	3.4E+03	3.4E+03	3.4E+03	3.9E+03	3.9E+03
Detroit, MI	3.4E+03	3.4E+03	3.4E+03	3.4E+03	3.4E+03
Columbus, OH	2.9E+03	2.9E+03	2.9E+03	2.9E+03	2.9E+03
Sacramento, CA	1.9E+03	1.9E+03	1.9E+03	1.9E+03	1.9E+03
Portland, OR	1.4E+03	1.4E+03	1.4E+03	1.6E+03	1.6E+03
Pittsburgh, PA	5.4E+02	5.4E+02	5.4E+02	5.4E+02	5.4E+02
Kansas City, MO	5.2E+02	5.2E+02	5.2E+02	5.2E+02	5.2E+02
Charlotte, NC	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Cleveland, OH	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Las Vegas, NV	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00

Table 39. Induced long-duration commuter residences accessible to UAM in five ATC ConOps scenarios.

Metropolitan Area	Induced Long-Duration Commuter Residence Coverage by ATC ConOps Scenario: Fully segregated from SUA and terminal airspace	Access to SUA	Access to airspace at low-traffic airports	Access to static VFR cutouts	Access to SUA, low-traffic airspace, & static VFR cutout
New York City, NY	3.9E+05	4.0E+05	3.9E+05	5.5E+05	6.1E+05
Chicago, IL	1.9E+05	2.2E+05	2.0E+05	2.2E+05	2.5E+05
Los Angeles, CA	1.5E+05	1.9E+05	1.5E+05	2.2E+05	2.7E+05
Boston, MA	1.2E+05	1.3E+05	1.5E+05	1.5E+05	1.9E+05
Atlanta, GA	9.4E+04	9.5E+04	9.8E+04	1.1E+05	1.1E+05
Philadelphia, PA	8.6E+04	8.9E+04	1.1E+05	9.7E+04	1.3E+05
Dallas, TX	7.0E+04	7.1E+04	7.9E+04	7.6E+04	8.9E+04
Seattle, WA	6.5E+04	6.6E+04	6.6E+04	8.0E+04	8.3E+04
San Francisco, CA	6.5E+04	8.9E+04	6.5E+04	9.1E+04	1.2E+05
Washington, DC	6.4E+04	1.1E+05	6.5E+04	8.1E+04	1.6E+05
Riverside, CA	6.4E+04	6.6E+04	6.4E+04	8.4E+04	8.6E+04
Houston, TX	6.0E+04	6.0E+04	6.7E+04	7.8E+04	8.6E+04
Baltimore, MD	4.9E+04	5.4E+04	4.9E+04	5.8E+04	6.3E+04
Miami, FL	4.1E+04	4.2E+04	4.1E+04	6.2E+04	6.6E+04
Detroit, MI	2.5E+04	2.5E+04	2.5E+04	2.8E+04	2.9E+04
Tampa, FL	2.3E+04	2.3E+04	2.3E+04	2.5E+04	2.5E+04
Minneapolis, MN	2.1E+04	2.2E+04	2.1E+04	2.2E+04	2.3E+04
Denver, CO	2.1E+04	2.2E+04	2.1E+04	2.7E+04	2.7E+04
Austin, TX	2.1E+04	2.1E+04	2.2E+04	2.2E+04	2.3E+04
Phoenix, AZ	2.0E+04	2.2E+04	2.0E+04	2.6E+04	2.8E+04
Pittsburgh, PA	2.0E+04	2.0E+04	2.3E+04	2.0E+04	2.3E+04
Portland, OR	2.0E+04	2.0E+04	2.0E+04	2.3E+04	2.4E+04
Sacramento, CA	1.8E+04	1.8E+04	1.8E+04	1.8E+04	1.8E+04
Charlotte, NC	1.8E+04	1.8E+04	1.8E+04	1.8E+04	1.8E+04
St. Louis, MO	1.6E+04	1.6E+04	1.6E+04	1.7E+04	1.8E+04
San Diego, CA	1.6E+04	1.6E+04	1.6E+04	2.0E+04	2.2E+04
Orlando, FL	1.5E+04	1.7E+04	1.5E+04	1.6E+04	2.0E+04
San Antonio, TX	1.4E+04	1.4E+04	1.5E+04	1.5E+04	1.7E+04
Cincinnati, OH	8.7E+03	8.9E+03	8.7E+03	9.1E+03	9.3E+03
Columbus, OH	8.3E+03	8.3E+03	8.5E+03	8.8E+03	9.0E+03
Indianapolis, IN	8.3E+03	8.3E+03	8.3E+03	8.5E+03	8.6E+03
Kansas City, MO	4.9E+03	4.9E+03	4.9E+03	4.9E+03	4.9E+03
Cleveland, OH	3.7E+03	3.7E+03	3.7E+03	3.7E+03	3.7E+03
Las Vegas, NV	6.5E+02	6.8E+02	6.5E+02	2.1E+03	2.2E+03

Additional Images of ATC Constructs and UAM Mission Coverage in the 34 MSAs

This section provides additional images of the UAM mission coverage analysis for each MSA from Chapter 9. Two images are provided for each MSA.

The left sub-images of Table 40 display the controlled airspace and SUA airspace constructs in red overtop a population density heat map of each MSA. The left sub-image therefore displays the "fully segregated" ATC ConOps scenario and provides a visual indication of where UAM aircraft could operate under VFR without any ATC scaling constraints today (i.e., the areas outside the red airspace constructs).

The right sub-images of Table 40 display the VFR separation minima around the 99.5th percentile containment boundaries for arrival and departure operations at high-traffic airports in each MSA. The right sub-image therefore corresponds to the "access to SUA, low traffic airspace, and static VFR cutouts" ATC ConOps scenario which simultaneous applies the three ATC integration strategies evaluated in this analysis. The right sub-image may be thought of as showing best-case UAM mission coverage for VFR operations.

Within each image, the boundary of the MSA in indicated by a magenta line, and major interstates and highways are plotted in grey for perspective.

Table 40. Additional images of ATC constructs and UAM mission coverage in the 34 MSAs

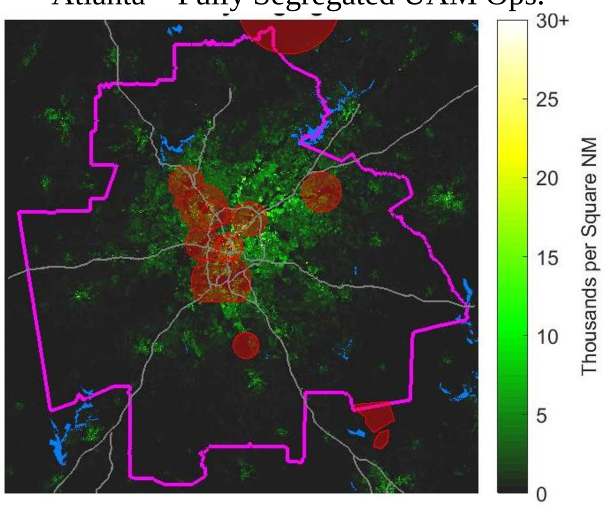
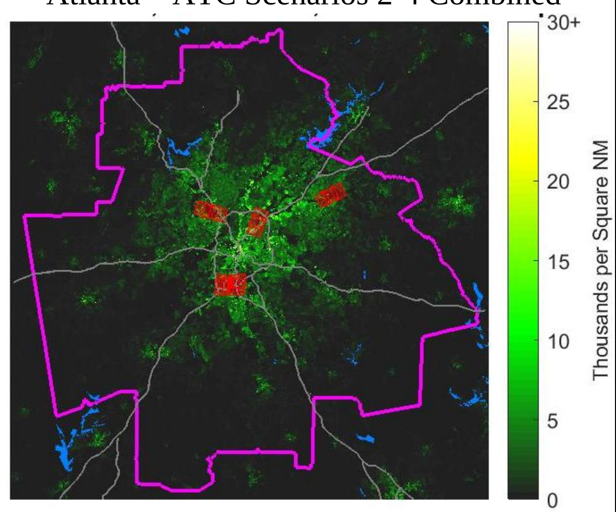
Atlanta – Fully Segregated UAM Ops.	Atlanta – ATC Scenarios 2-4 Combined
	

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Table 40 (continued). Images of ATC constructs and UAM mission coverage in the 34 MSAs

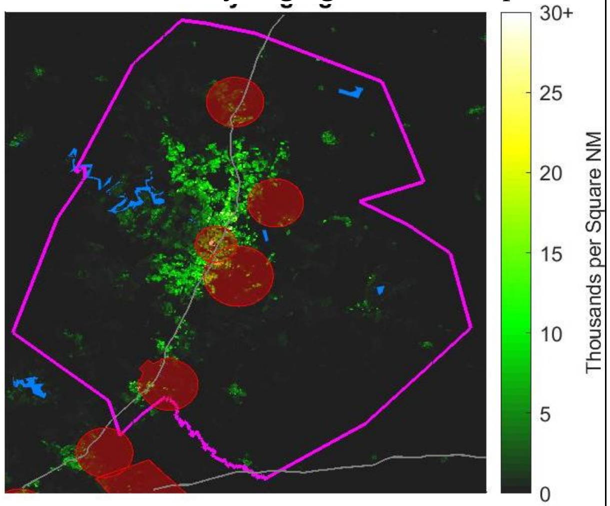
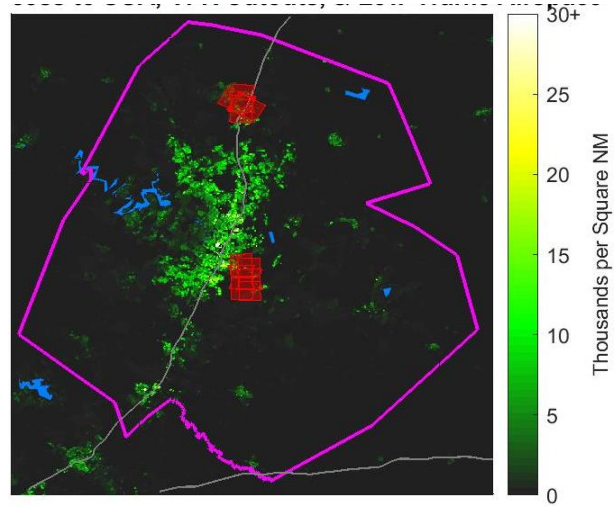
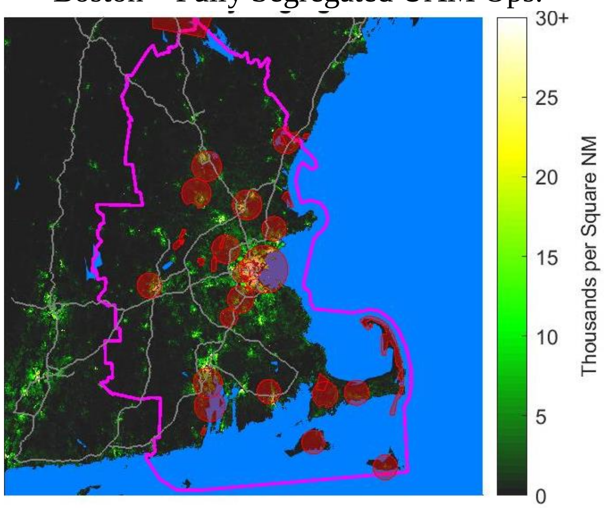
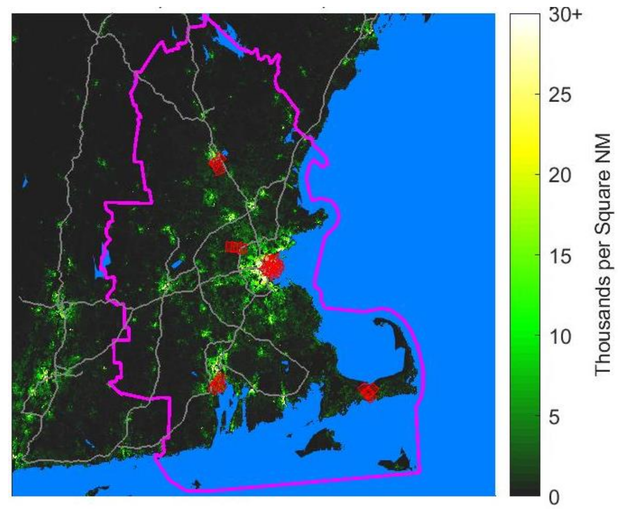
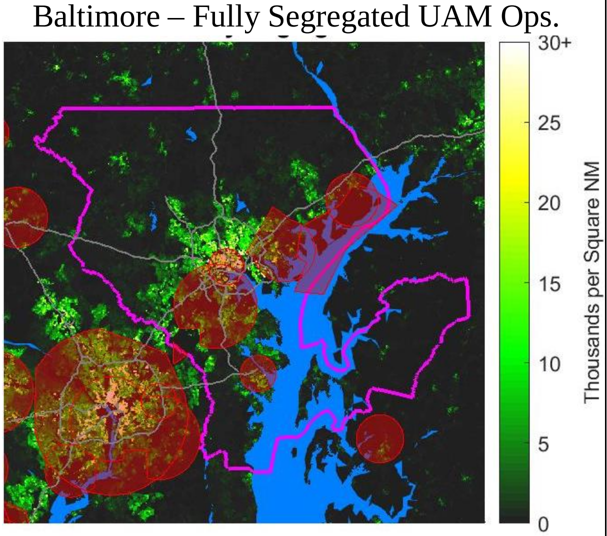
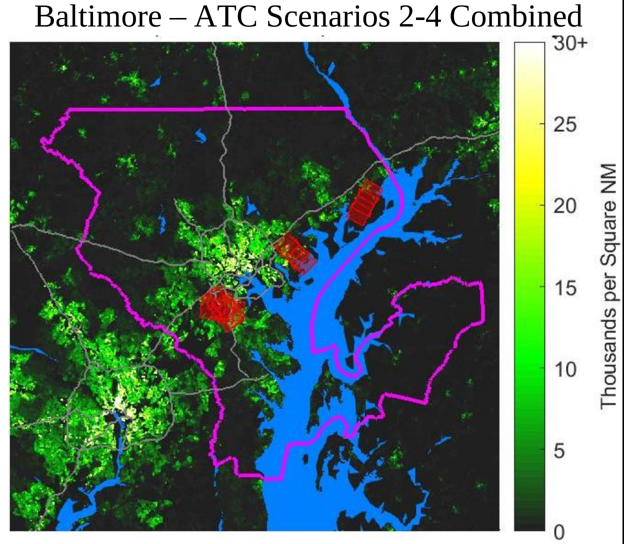
Austin – Fully Segregated UAM Ops.  	Austin – ATC Scenarios 2-4 Combined 
Boston – Fully Segregated UAM Ops.  	Boston – ATC Scenarios 2-4 Combined 
Baltimore – Fully Segregated UAM Ops.  	Baltimore – ATC Scenarios 2-4 Combined 

Table 40 (continued). Images of ATC constructs and UAM mission coverage in the 34 MSAs

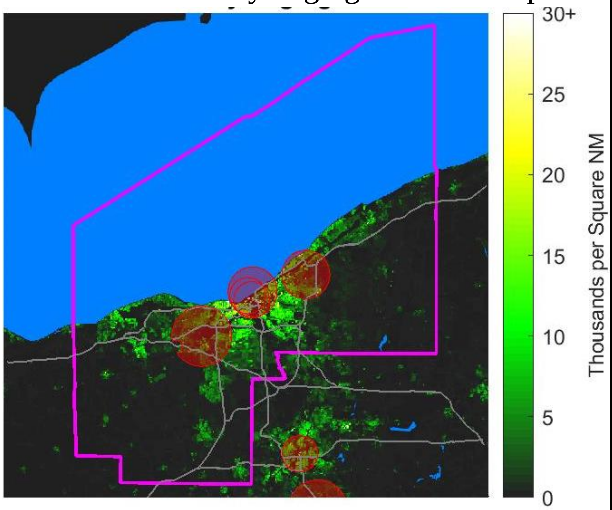
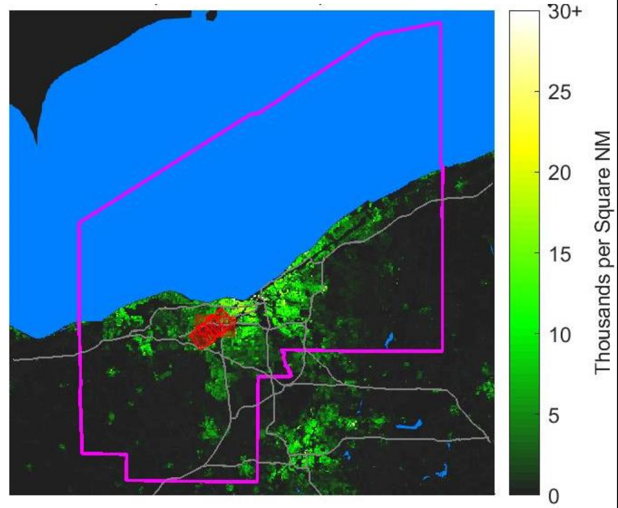
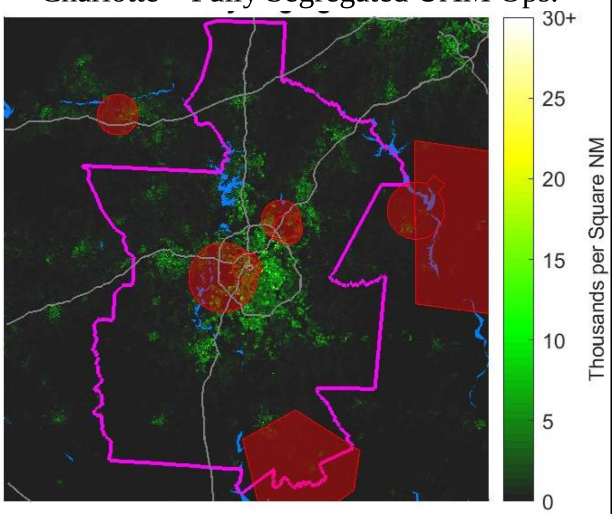
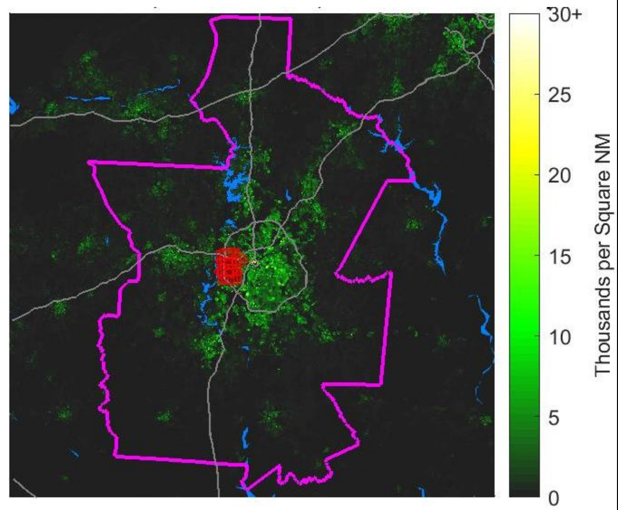
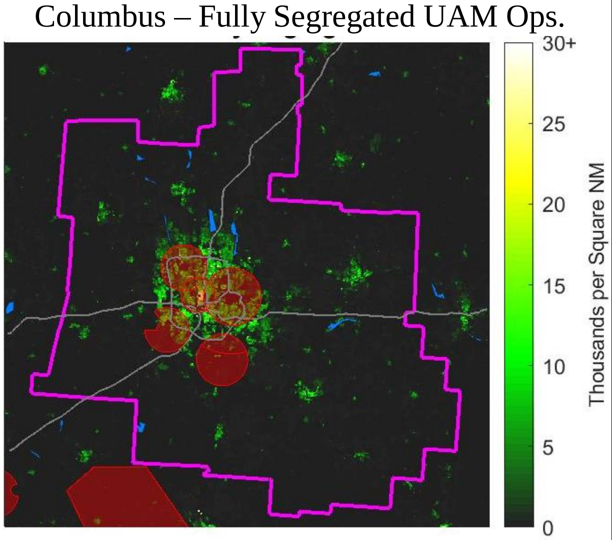
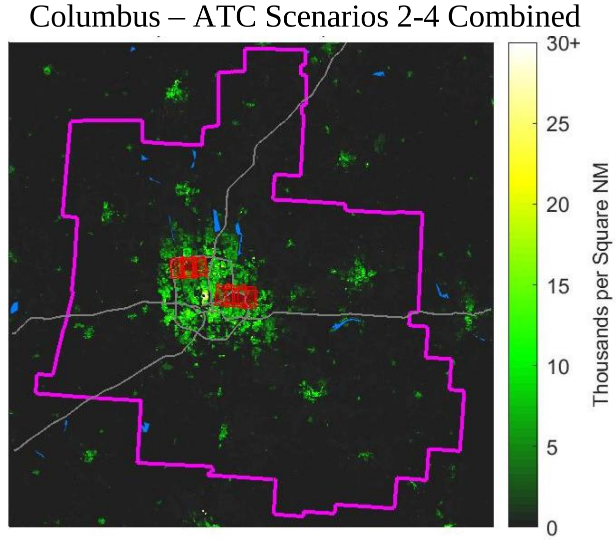
Cleveland – Fully Segregated UAM Ops.	Cleveland – ATC Scenarios 2-4 Combined
	
Charlotte – Fully Segregated UAM Ops.	Charlotte – ATC Scenarios 2-4 Combined
	
Columbus – Fully Segregated UAM Ops.	Columbus – ATC Scenarios 2-4 Combined
	

Table 40 (continued). Images of ATC constructs and UAM mission coverage in the 34 MSAs

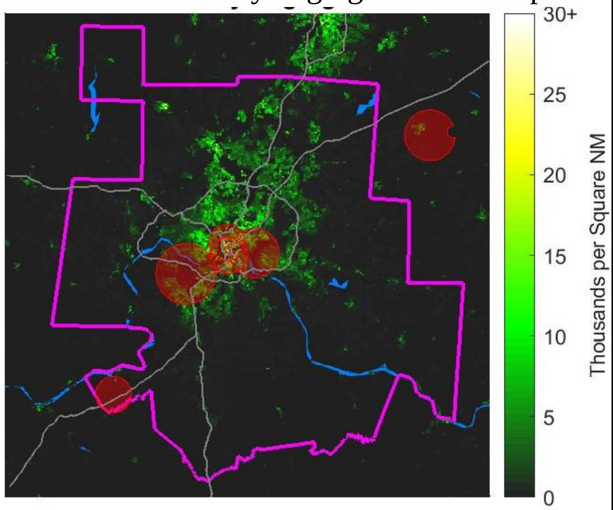
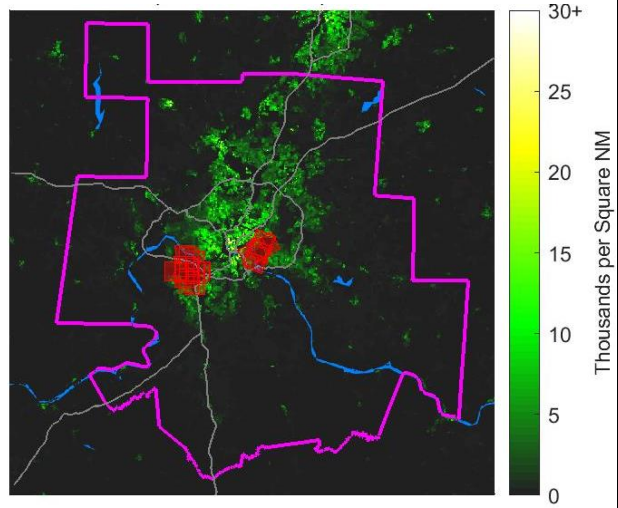
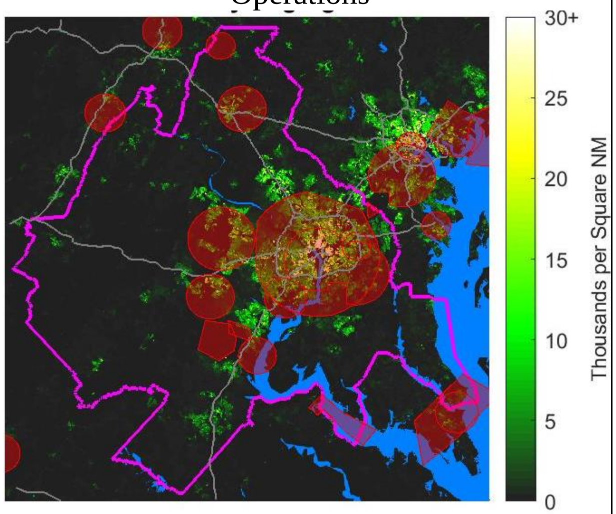
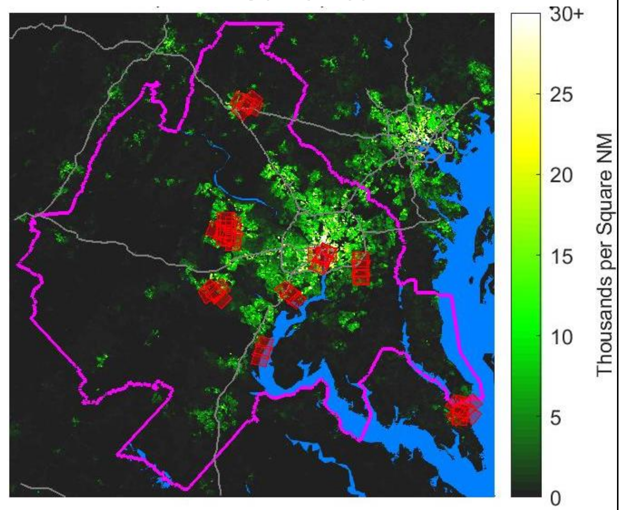
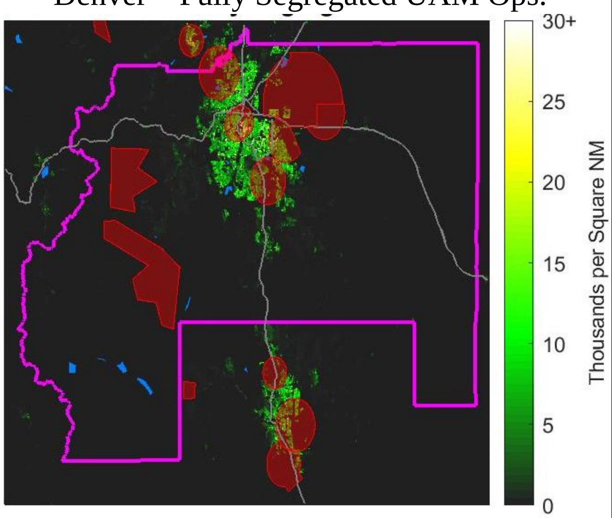
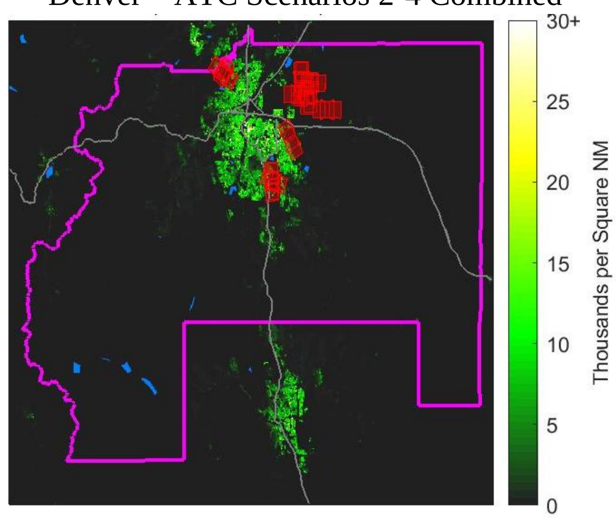
Cincinnati – Fully Segregated UAM Ops.  	Cincinnati – ATC Scenarios 2-4 Combined 
Washington DC – Fully Segregated UAM Operations  	Washington DC – ATC Scenarios 2-4 Combined 
Denver – Fully Segregated UAM Ops.  	Denver – ATC Scenarios 2-4 Combined 

Table 40 (continued). Images of ATC constructs and UAM mission coverage in the 34 MSAs

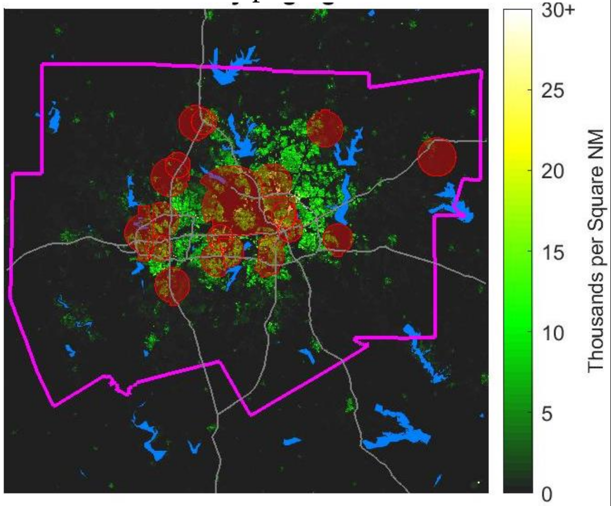
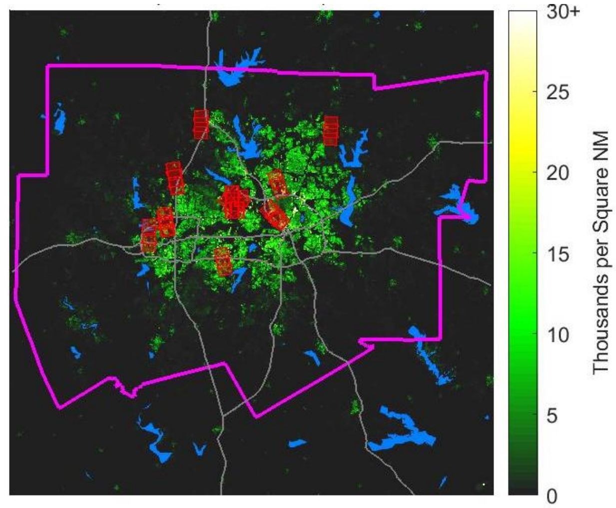
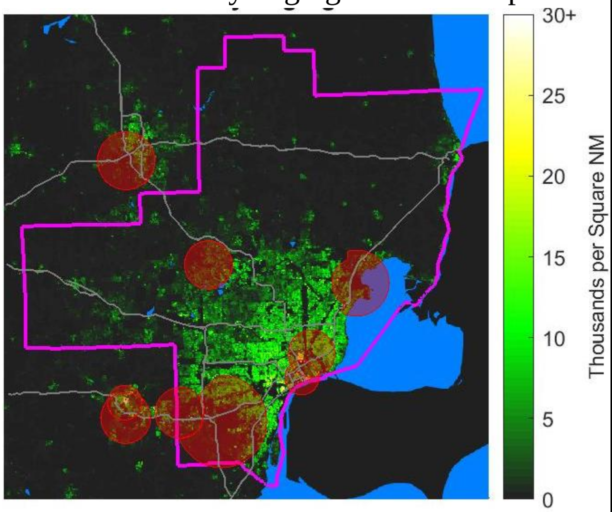
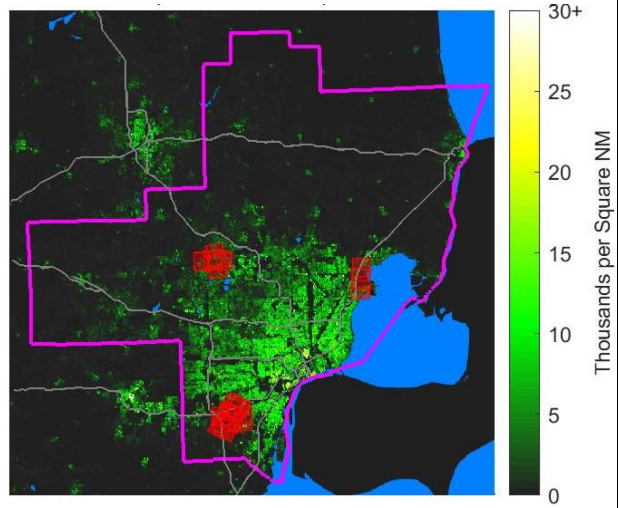
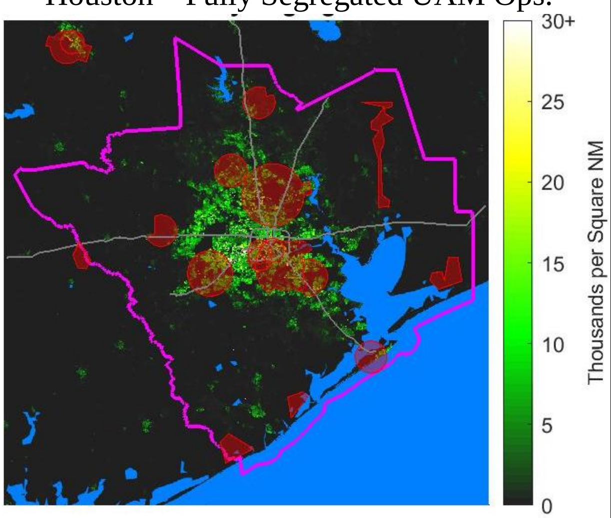
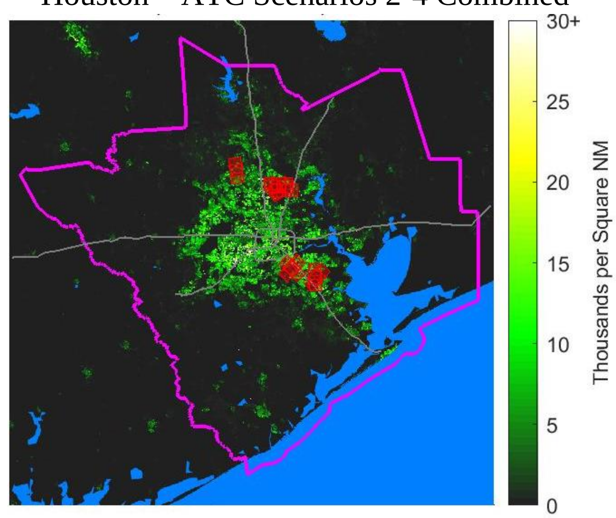
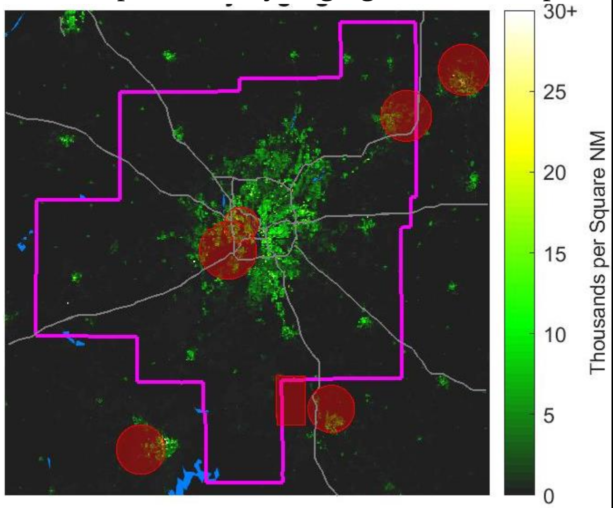
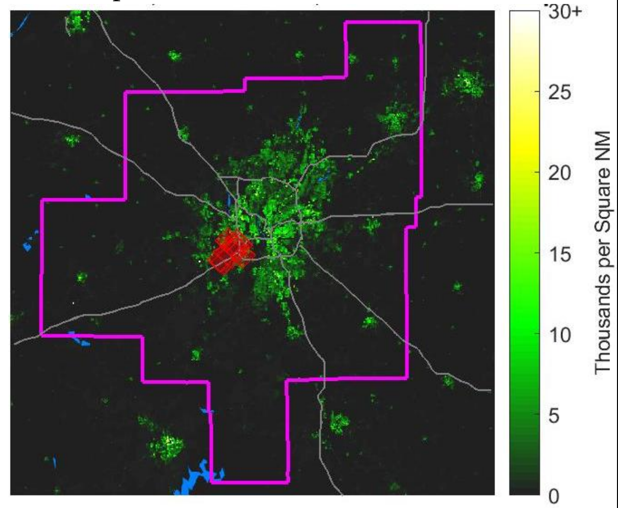
Dallas-Fort Worth – Fully Segregated UAM Operations	Dallas-Fort Worth – ATC Scenarios 2-4 Combined
	
Detroit – Fully Segregated UAM Ops.	Detroit – ATC Scenarios 2-4 Combined
	
Houston – Fully Segregated UAM Ops.	Houston – ATC Scenarios 2-4 Combined
	

Table 40 (continued). Images of ATC constructs and UAM mission coverage in the 34 MSAs

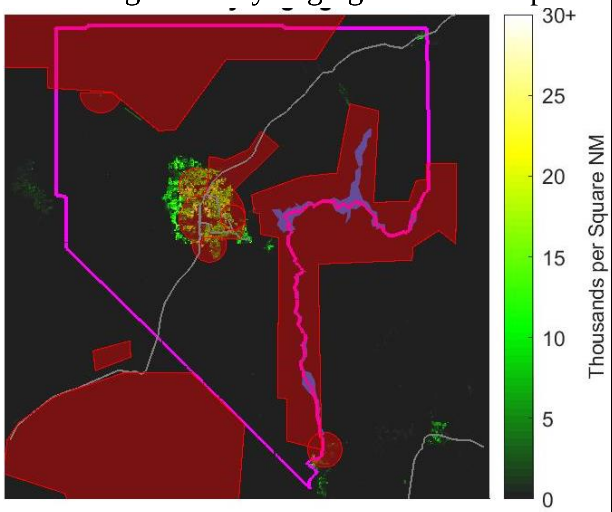
Indianapolis – Fully Segregated UAM Ops.



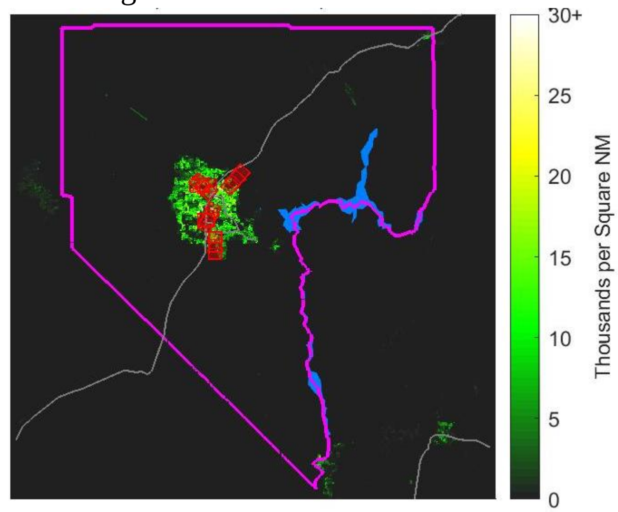
Indianapolis – ATC Scenarios 2-4 Combined



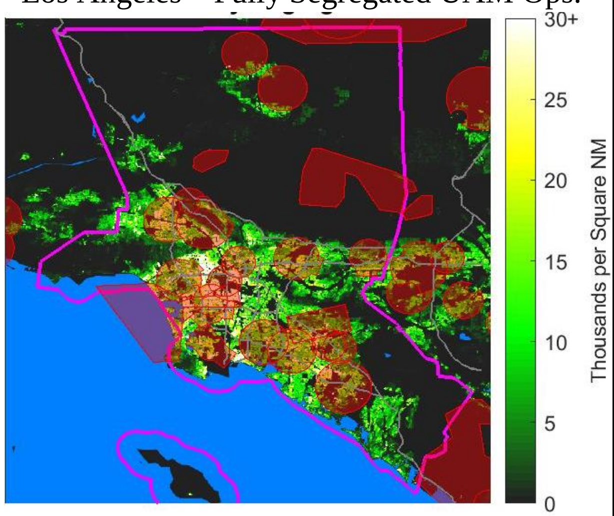
Las Vegas – Fully Segregated UAM Ops.



Las Vegas – ATC Scenarios 2-4 Combined



Los Angeles – Fully Segregated UAM Ops.



Los Angeles – ATC Scenarios 2-4 Combined

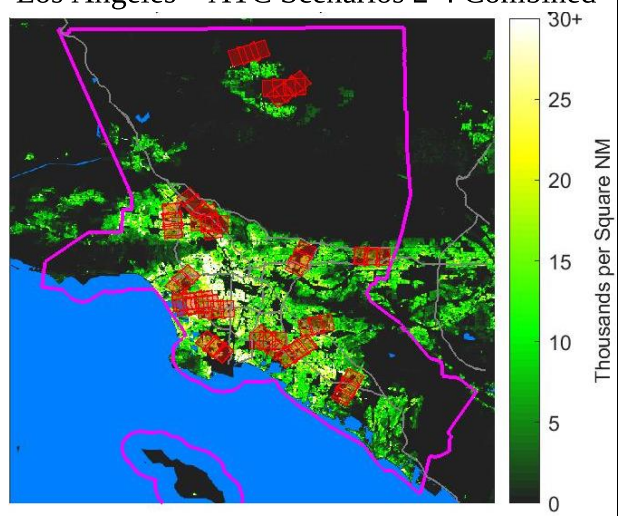


Table 40 (continued). Images of ATC constructs and UAM mission coverage in the 34 MSAs

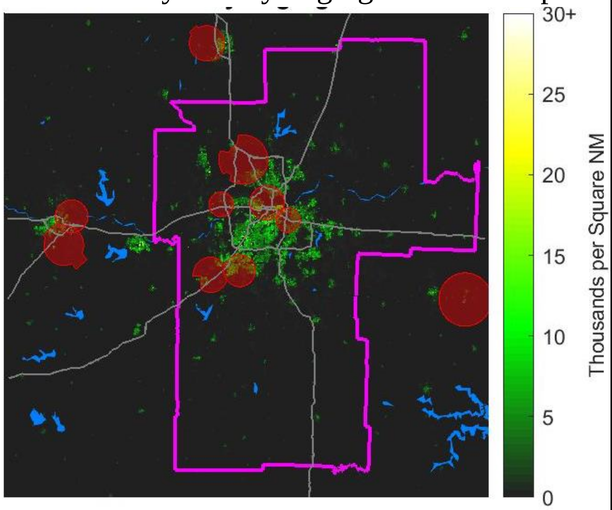
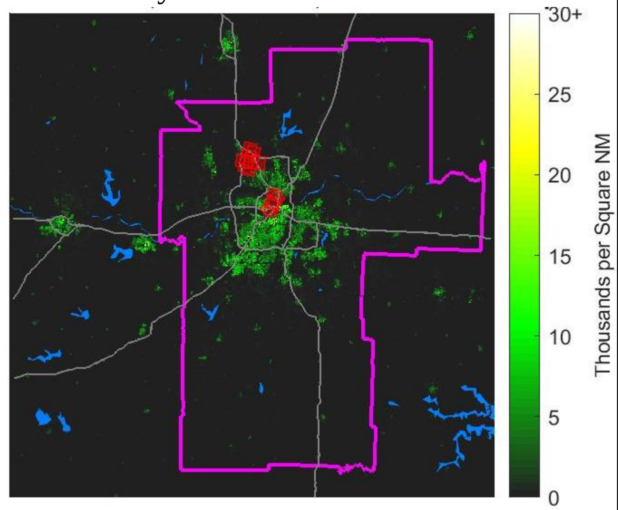
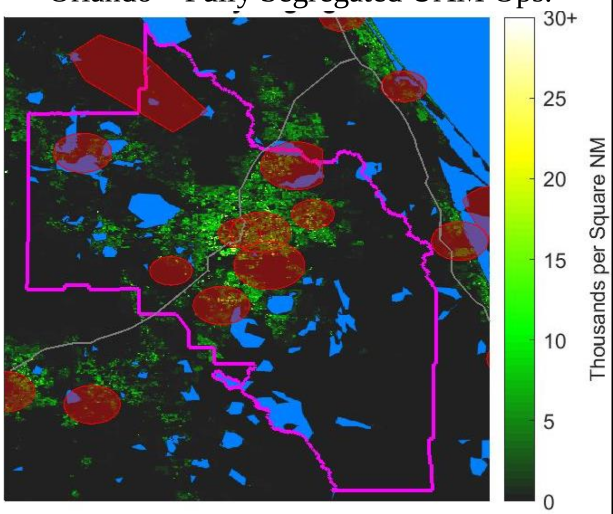
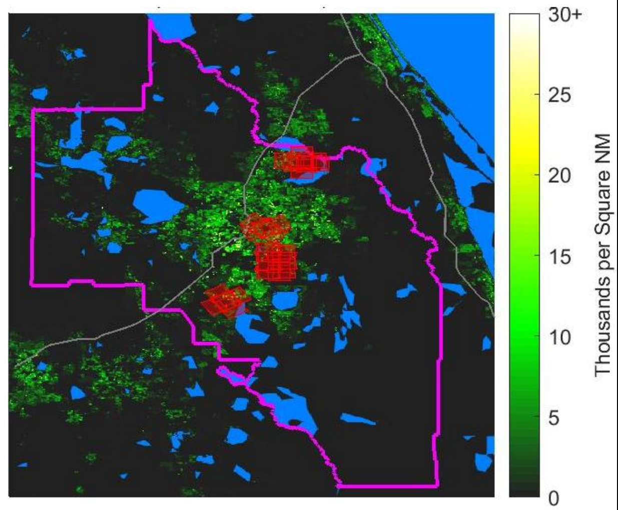
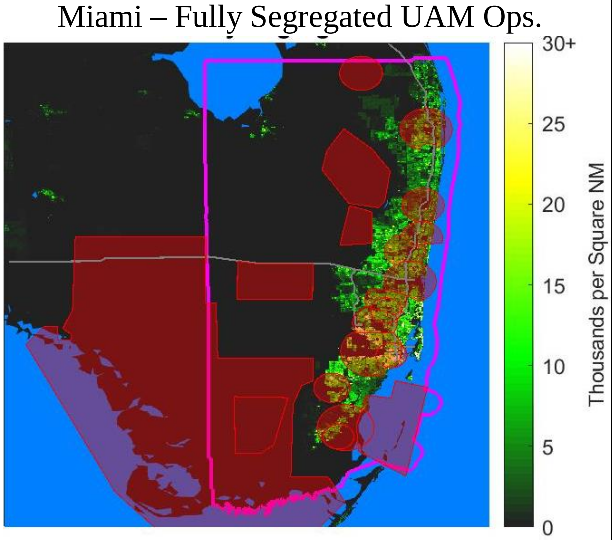
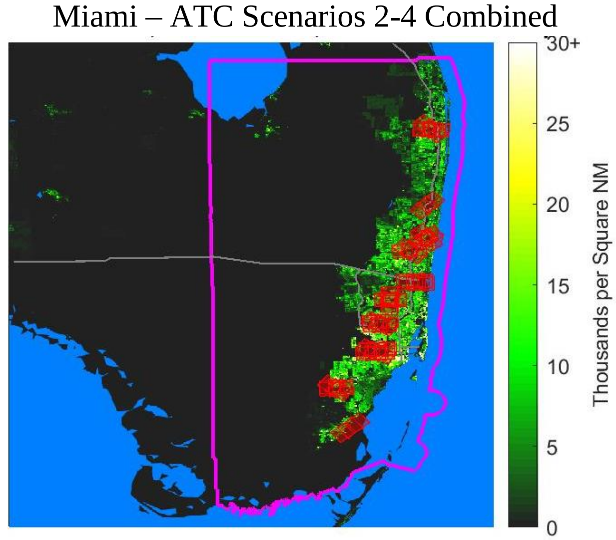
Kansas City – Fully Segregated UAM Ops. 	Kansas City – ATC Scenarios 2-4 Combined 
Orlando – Fully Segregated UAM Ops. 	Orlando – ATC Scenarios 2-4 Combined 
Miami – Fully Segregated UAM Ops. 	Miami – ATC Scenarios 2-4 Combined 

Table 40 (continued). Images of ATC constructs and UAM mission coverage in the 34 MSAs

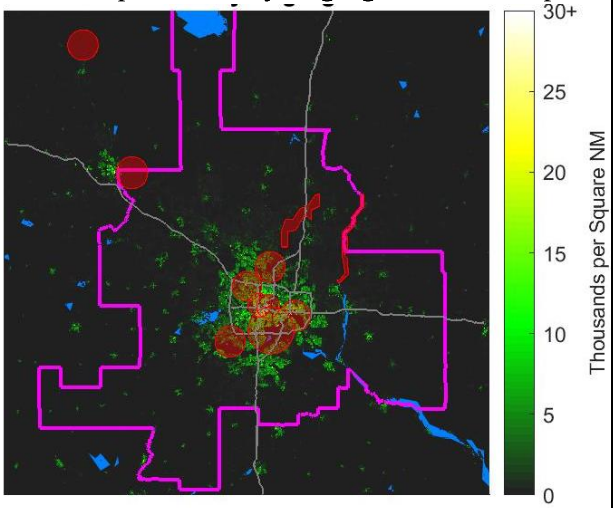
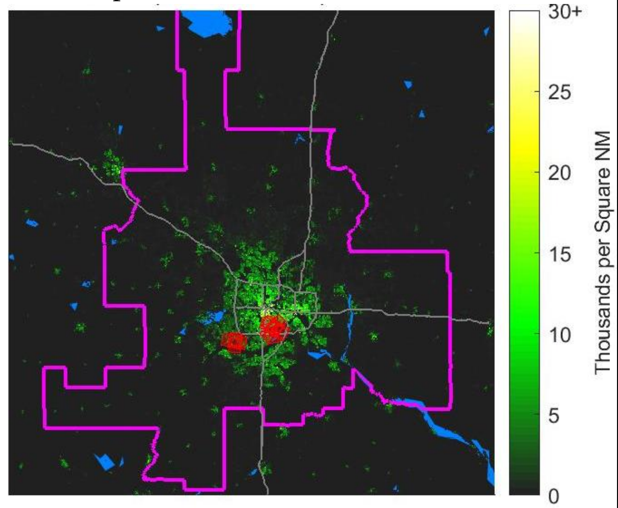
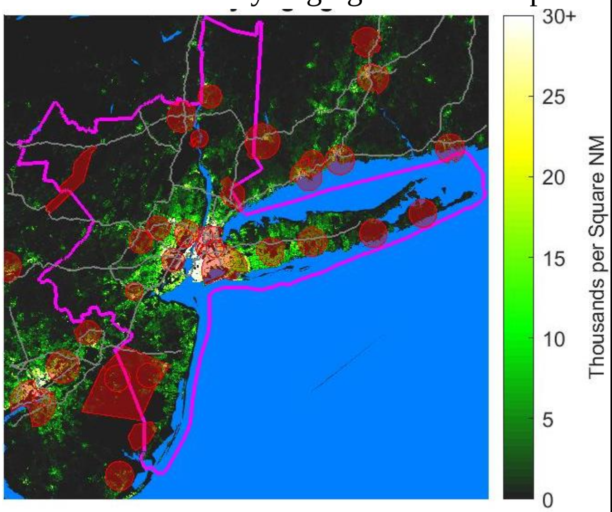
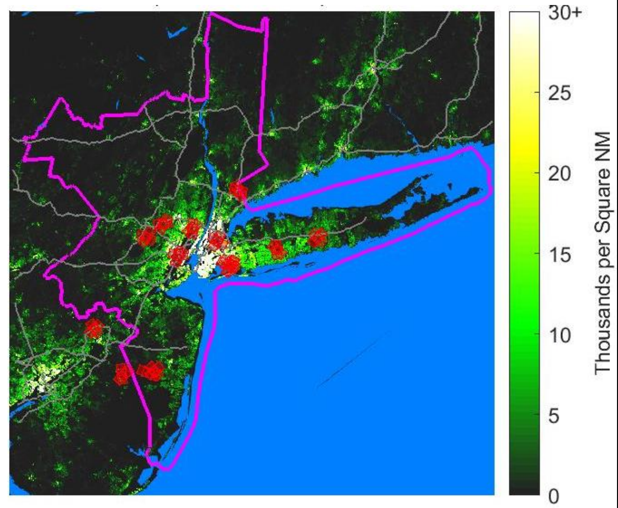
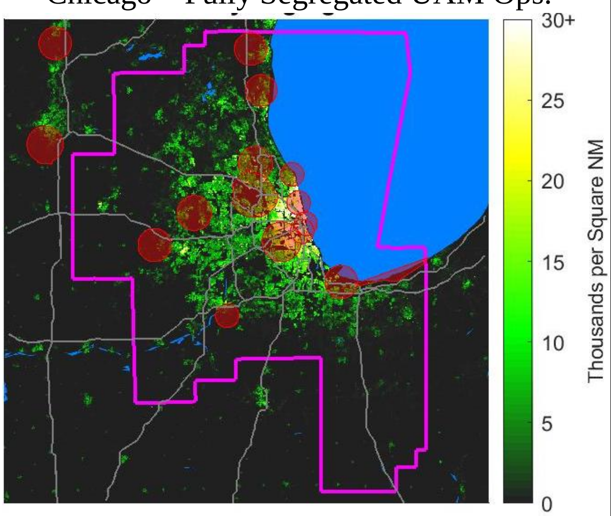
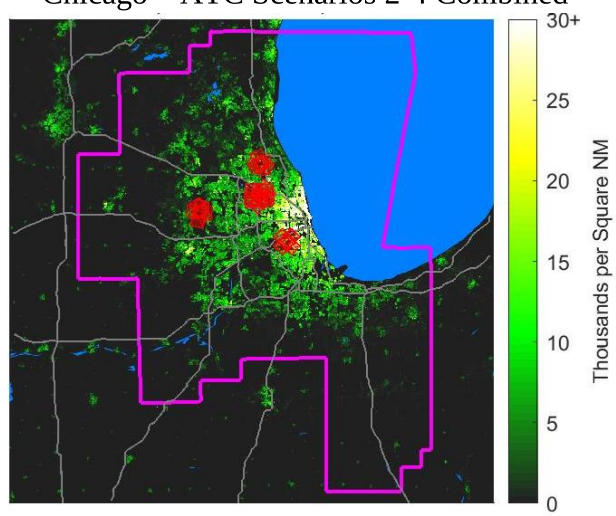
Minneapolis – Fully Segregated UAM Ops.	Minneapolis – ATC Scenarios 2-4 Combined
	
New York – Fully Segregated UAM Ops.	New York – ATC Scenarios 2-4 Combined
	
Chicago – Fully Segregated UAM Ops.	Chicago – ATC Scenarios 2-4 Combined
	

Table 40 (continued). Images of ATC constructs and UAM mission coverage in the 34 MSAs

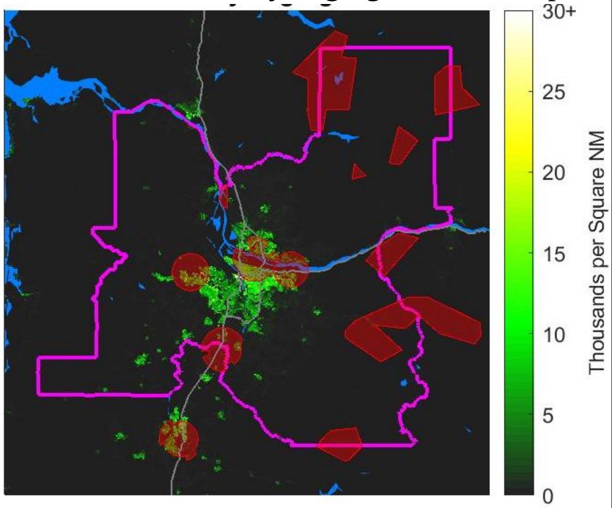
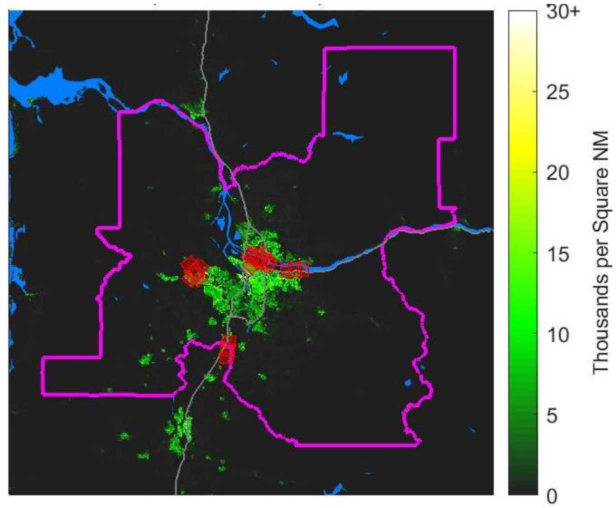
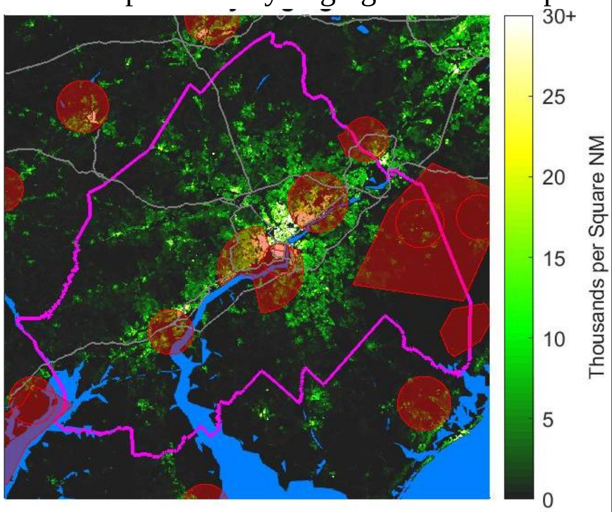
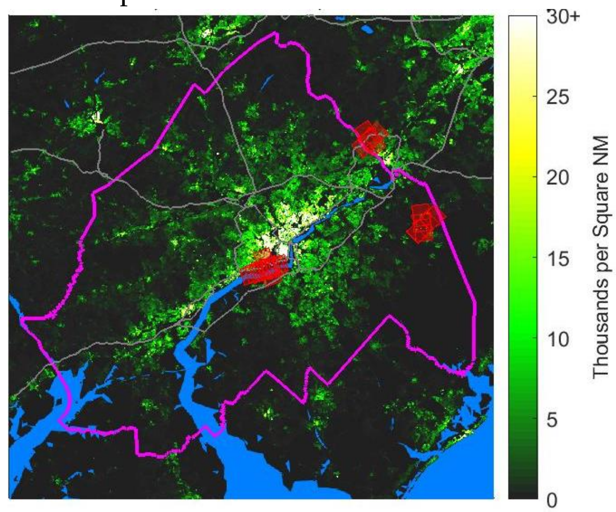
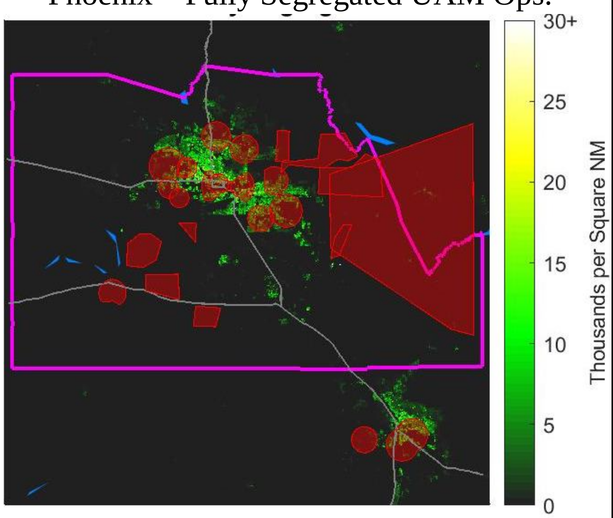
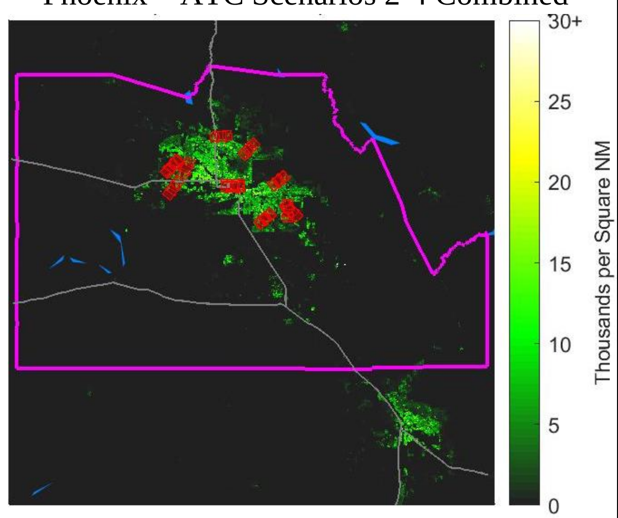
Portland, OR – Fully Segregated UAM Ops.  	Portland, OR – ATC Scenarios 2-4 Combined 
Philadelphia – Fully Segregated UAM Ops.  	Philadelphia – ATC Scenarios 2-4 Combined 
Phoenix – Fully Segregated UAM Ops.  	Phoenix – ATC Scenarios 2-4 Combined 

Table 40 (continued). Images of ATC constructs and UAM mission coverage in the 34 MSAs

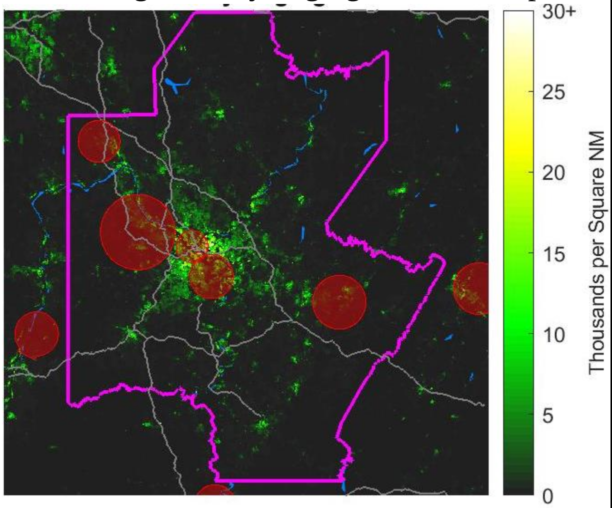
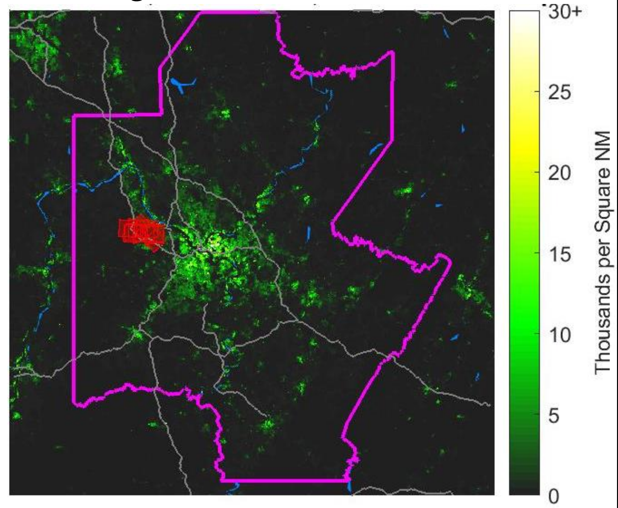
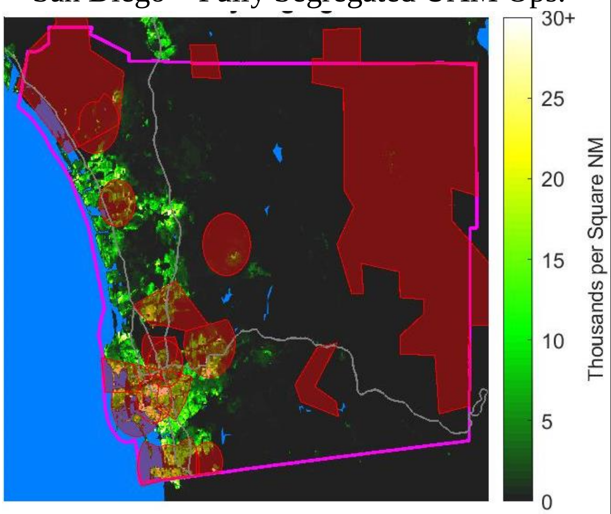
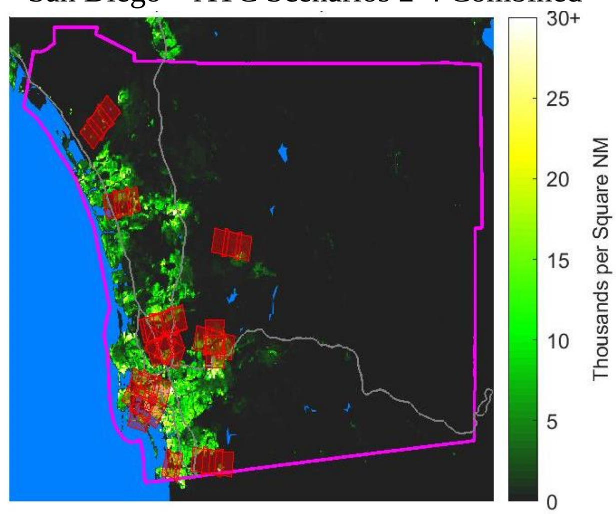
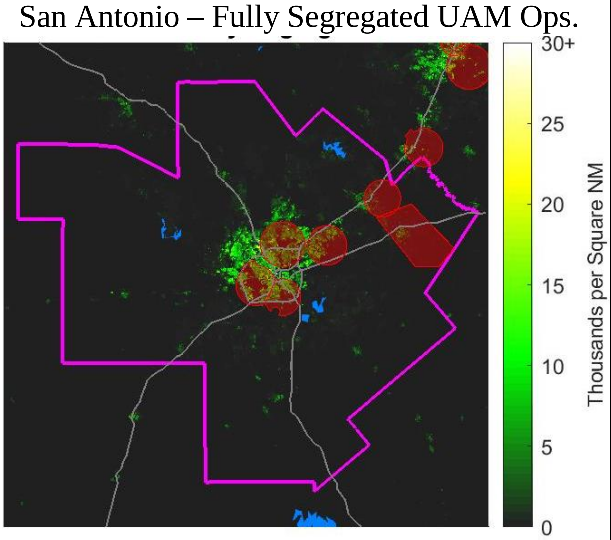
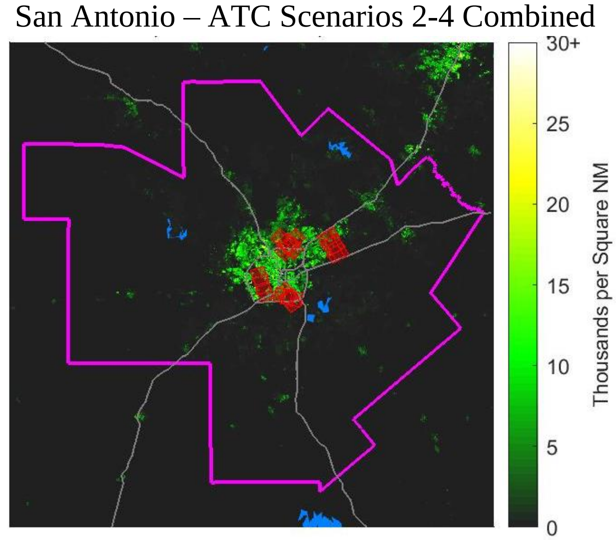
Pittsburgh – Fully Segregated UAM Ops.	Pittsburgh – ATC Scenarios 2-4 Combined
	
San Diego – Fully Segregated UAM Ops.	San Diego – ATC Scenarios 2-4 Combined
	
San Antonio – Fully Segregated UAM Ops.	San Antonio – ATC Scenarios 2-4 Combined
	

Table 40 (continued). Images of ATC constructs and UAM mission coverage in the 34 MSAs

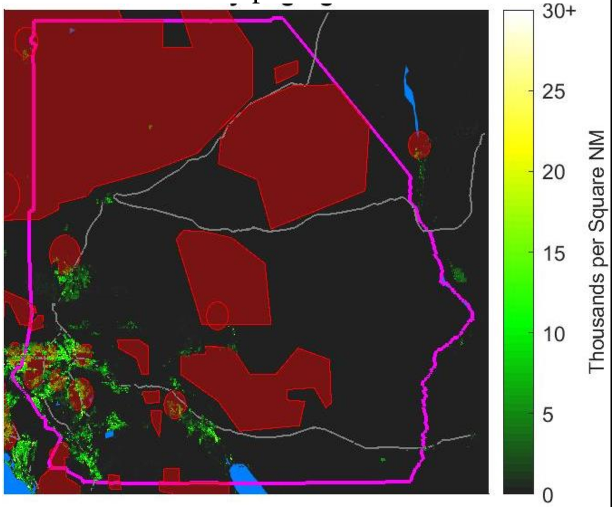
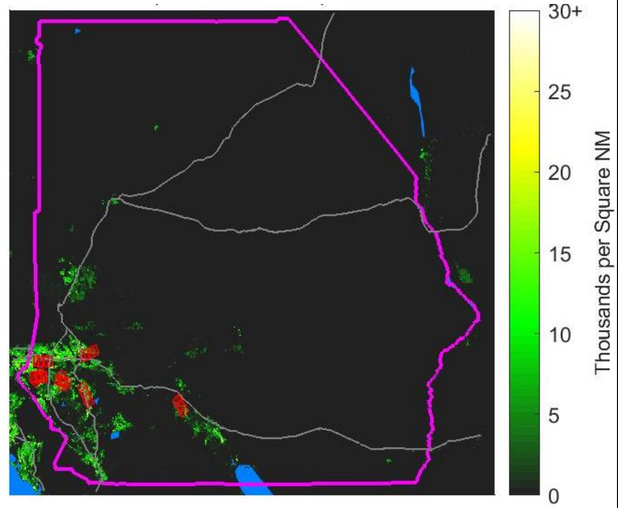
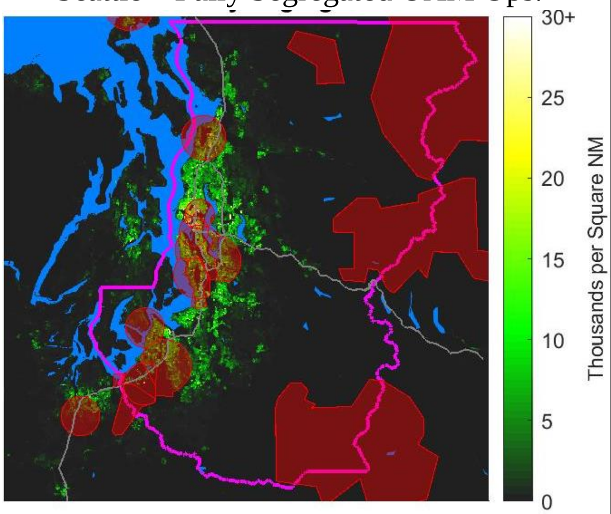
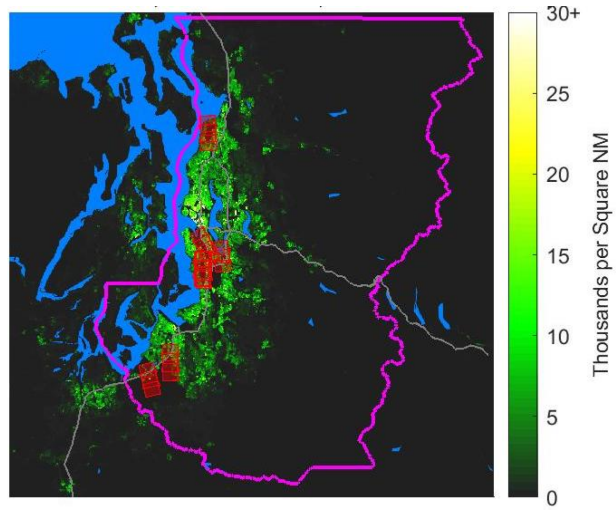
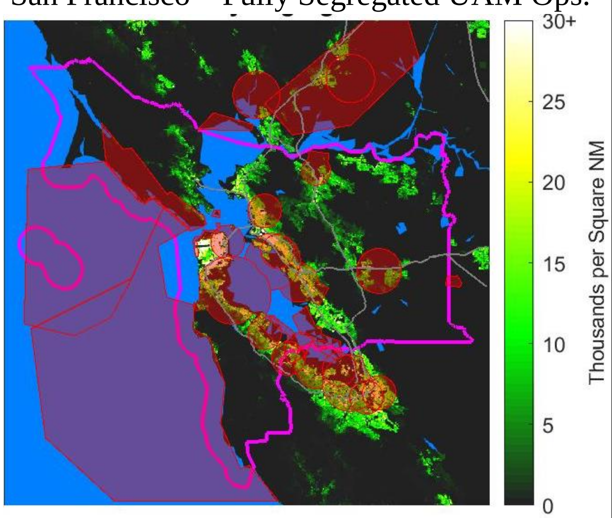
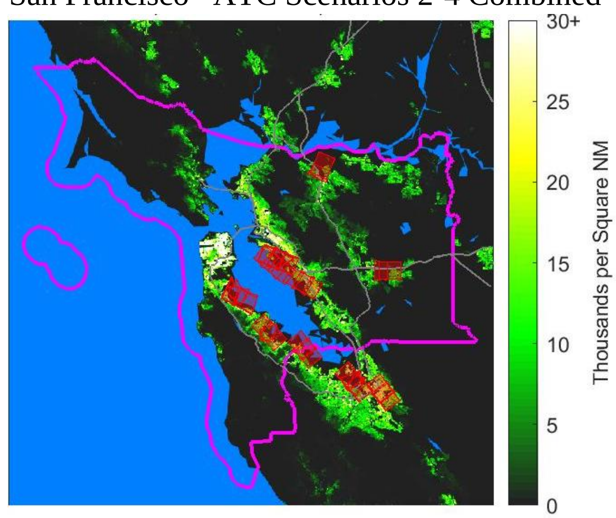
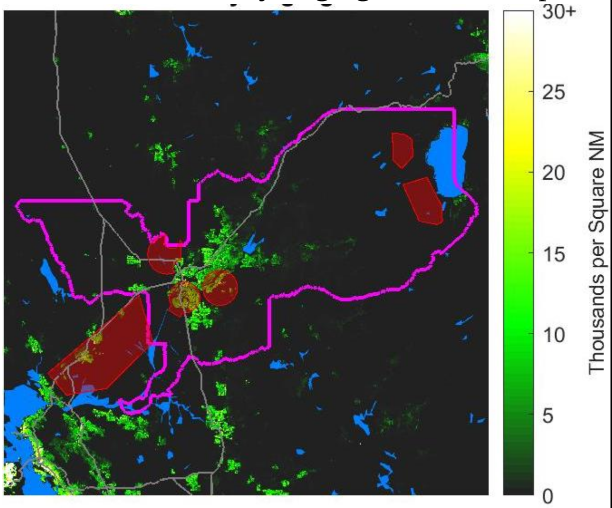
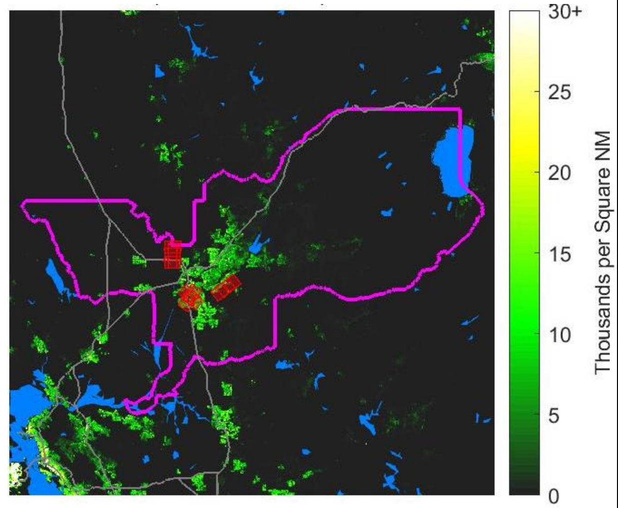
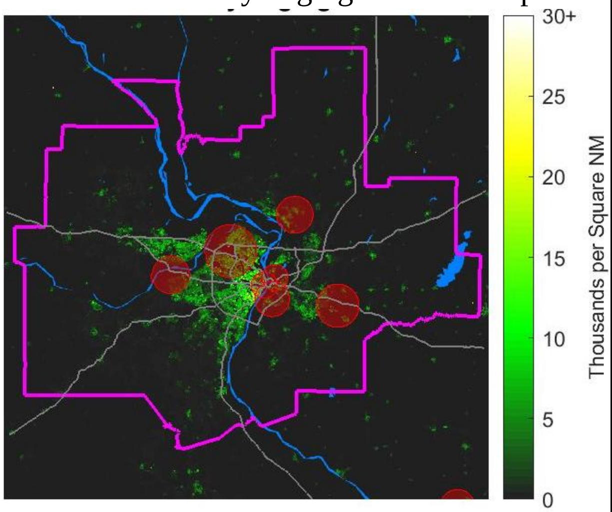
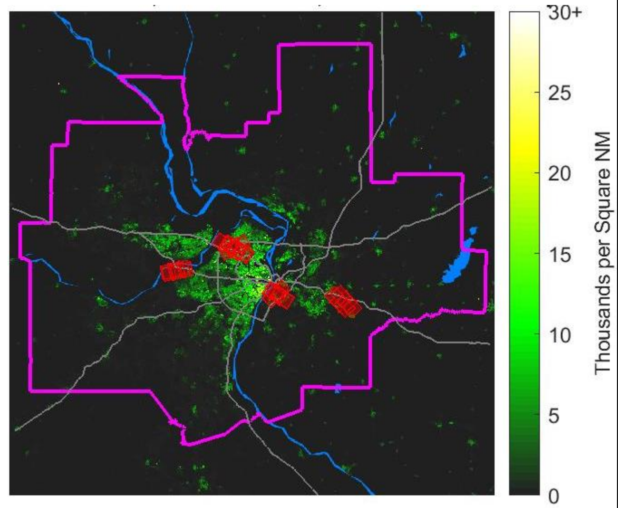
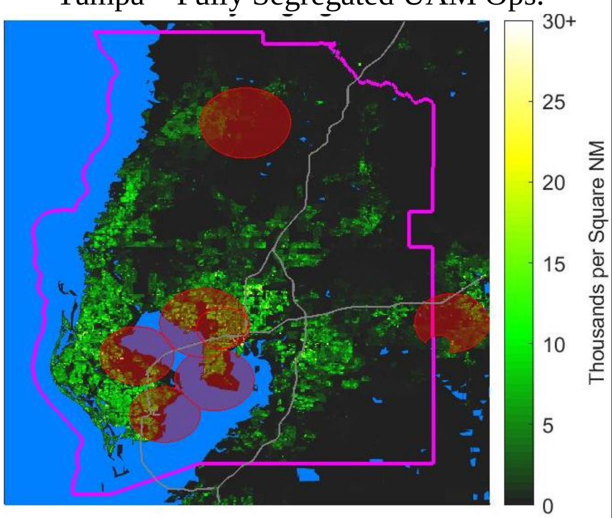
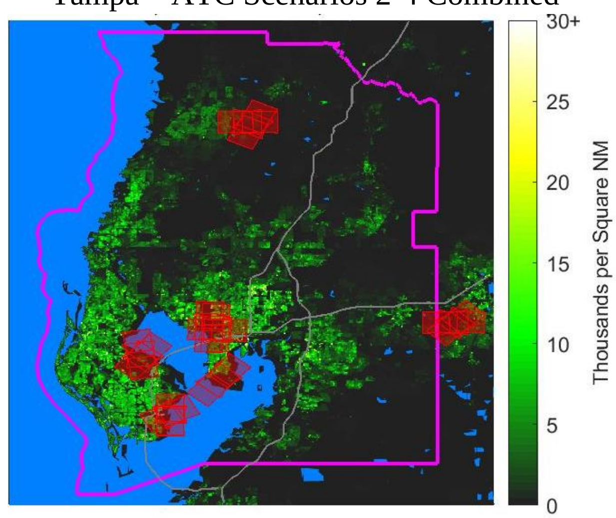
San Bernardino – Fully Segregated UAM Operations  	San Bernardino – ATC Scenarios 2-4 Combined 
Seattle – Fully Segregated UAM Ops.  	Seattle – ATC Scenarios 2-4 Combined 
San Francisco – Fully Segregated UAM Ops.  	San Francisco– ATC Scenarios 2-4 Combined 

Table 40 (continued). Images of ATC constructs and UAM mission coverage in the 34 MSAs

Sacramento – Fully Segregated UAM Ops.  	Sacramento – ATC Scenarios 2-4 Combined 
St. Louis – Fully Segregated UAM Ops.  	St. Louis – ATC Scenarios 2-4 Combined 
Tampa – Fully Segregated UAM Ops.  	Tampa – ATC Scenarios 2-4 Combined 

Airport Analysis

Based upon the analysis of UAM airport interoperability conducted in Chapter 8, the following attributes of airports were determined to influence the ease of UAM integration at airports:

- Frequency of IFR Operations: IMC with ceilings below 1000 ft AGL or visibility below 0.5 NM will require UAM aircraft classified as helicopters to operate under IFR. IFR significantly increases the challenge of supporting UAM operations at airports by increasing the distance which UAM arrivals and departure must be separated from conventional runways.
- Distance of Terminal to Nearest Runway: UAM flights directly to the airport terminals are desired to increase the efficiency of the service and to minimize surface transportation logistics. Terminals spaced 2500 ft from the nearest runway may support simultaneous VFR UAM and conventional aircraft operations as well as IFR departures.
- Potential Site for Widely-Spaced VFR TOLA on Airport Boundary: Even if the passenger terminal is not spaced 2500 ft from the runways, it is still beneficial to have a location on the airport to which VFR arrivals and departures may be conducted in a non-interfering manner. Ground transportation from the TOLA to the terminal would be required.
- Imbedded Terminal: UAM access to terminals, especially in instrument conditions, is more difficult if the passenger terminal is imbedded between parallel or near-parallel runways. Terminals located outside the runways may support converging UAM arrivals or departures, while imbedded terminals require parallel operations.
- Crossing Runways: Airports with crossing conventional runways increase the complexity of the terminal airspace. Multiple different approach and departure routes for UAM operations may be required based upon the wind direction and flow pattern of the airports. Furthermore, a single TOLA location may not provide the appropriate separation in all airport flow patterns.
- Airport Imbedded within Densely Populated Area: Airports that are surrounded on all sides by dense populations may be more challenging for UAM integration. Airports abutting water bodies or undeveloped land may potentially support point in space approaches and low altitude air taxiing over these areas to simplify UAM integration in IFR or VFR conditions. However, such low altitude flight operations may not be possible or tolerated by the community if the areas are densely populated.

The major airports (i.e., airports with class B or Class C airspace) in each MSA were evaluated based on these six qualities. The purpose of the review of airports was to provide an impression of scaling limitations for an airport shuttle UAM service in each MSA; this was intended to supplement the ATC constraint impacts presented in the previous sections in order to identify promising early adopting markets for UAM services.

Table 41 displays the results of the airport analysis for the 49 major commercial airports in the 34 MSAs. The cells have been highlighted red or green to indicate beneficial or negative characteristics for UAM interoperability. Airports that required UAM IFR operations less frequently than the median value of 6.6% were colored green.

A number of interesting features may be drawn from Table 41. First, no airport was found with only beneficial attributes for UAM integration. San Francisco International Airport (SFO), Sacramento International Airport (SMF), and San Diego International Airport (SAN) were perceived as the simplest airports to integrate UAM, based upon these metrics. These airports all experienced a low frequency of required IFR, but otherwise were quite different in topology. SFO had crossing runways, SMF had widely spaced parallel runways with an imbedded terminal, and SAN had a single runway with a small airport footprint that necessitated the siting of the UAM TOLA away from the terminal. The differences in these airports indicates that there is not a common airport topology that indicates ease of interoperability with UAM.

The airports perceived as most challenging for UAM integration were Chicago Midway International Airport (MDW) and LaGuardia International Airport (LGA). These airports were both located on comparatively small footprints in densely populated areas. Furthermore, airports located in the northeast were generally found to be more difficult for UAM integration due to the prevalence of crossing runways, imbedded terminals, and IFR at these airports. All three of these factors are the result of more variable weather conditions compared to the west coast airports, as well as the older age of the airports and development for aircraft with less cross-wind tolerance.

Despite their limitations, VFR UAM integration was anticipated to be feasible at both MDW and LGA through diverging departures and converging arrival to crossing runways or closely spaced TOLA infrastructure. High-throughput IFR integration, however, would likely not be possible at these airports.

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Table 41. Analysis of UAM airport integration attributes for the major commercial airports in the 34 MSAs.

MSA	Major Airports	% of Time Hard IMC	Distance of Terminal to Nearest Runway (ft)	Potential Site for Widely Spaced VFR TOLA?	Imbedded Terminal?	Crossing Runways?	Imbedded within Developed Area?
Seattle	KSEA	6.4%	1900	Yes	No	No	Yes
Portland	KPDX	3.7%	1500	Yes	Yes	Yes	No
Sacramento	KSMF	4.1%	2800	Yes	Yes	No	No
San Francisco	KSFO	4.0%	3000	Yes	No	Yes	No
	KOAK	6.1%	3500	Yes	Yes	No	No
Los Angeles	KLAX	6.6%	2300	No	Yes	No	No
	KBUR	3.1%	500	Yes	No	Yes	Yes
	KSNA	4.0%	1100	No	No	No	Yes
San Diego	KSAN	4.9%	2000	Yes	No	No	No
Riverside	KONT	1.9%	1500	No	No	No	Yes
Las Vegas	KLAS	0.2%	3500	Yes	No	Yes	Yes
Phoenix	KPHX	0.1%	1600	Yes	Yes	No	Yes
Denver	KDEN	5.4%	3000	Yes	Yes	Yes	No
Minneapolis	KMSP	6.0%	1600	Yes	Yes	Yes	No
Kansas City	KMCI	6.7%	1500	Yes	Yes	Yes	No
St. Louis	KSTL	5.2%	1800	No	No	Yes	Yes
Chicago	KORD	7.7%	2500	Yes	Yes	Yes	Yes
	MDW	7.4%	1700	No	No	Yes	Yes
Indianapolis	KIND	6.6%	2400	Yes	Yes	No	No
Cincinnati	KCVG	6.4%	2600	Yes	Yes	Yes	No
Columbus	KCMH	4.4%	1400	Yes	Yes	No	Yes
Cleveland	KCLE	5.6%	2000	Yes	No	Yes	No
Detroit	KDTW	6.3%	1800	No	Yes	Yes	No
Pittsburgh	KPIT	6.3%	2100	Yes	Yes	Yes	No
Boston	KBOS	9.2%	2500	Yes	No	Yes	No
	KMHT	9.9%	1800	Yes	Yes	Yes	No
	KPVD	10.3%	2000	Yes	No	Yes	Yes
New York	KLGA	6.7%	1800	No	No	Yes	Yes
	KJFK	7.7%	3300	Yes	Yes	Yes	No
	KEWR	7.2%	2500	Yes	No	Yes	Yes
	KISP	11.9%	1400	Yes	No	Yes	No
Philadelphia	KPHL	6.7%	2700	Yes	No	Yes	No
Baltimore	KBWI	7.4%	1800	Yes	Yes	Yes	Yes
Washington, DC	KDCA	5.8%	1400	Yes	No	Yes	No
	KIAD	8.2%	3300	Yes	Yes	Yes	No
Charlotte	KCLT	9.2%	2300	Yes	Yes	Yes	No
Atlanta	KATL	8.6%	2200	Yes	Yes	No	Yes
Tampa	KTPA	3.0%	1900	No	Yes	Yes	No
Orlando	KMCO	3.6%	3800	Yes	Yes	No	No
	KSFB	4.4%	2200	Yes	No	Yes	No
Miami	KMIA	0.9%	2400	Yes	Yes	Yes	Yes
	KFLL	0.7%	1900	No	Yes	No	Yes
	KPBI	1.0%	2500	Yes	No	Yes	Yes
Dallas	KDFW	4.8%	3100	Yes	Yes	Yes	Yes
	KDAL	4.7%	1100	No	Yes	No	Yes
Austin	KAUS	8.1%	2800	Yes	Yes	Yes	No
San Antonio	KSAT	9.5%	1700	Yes	No	Yes	Yes
Houstin	KHOU	6.6%	2000	Yes	No	Yes	Yes
	KIAH	7.2%	2500	Yes	Yes	Yes	Yes

Appendix E: Exploratory Case Study Reference Missions

The 12 reference missions defined for the Los Angeles city case are summarized in Table 42 and plotted in Fig. 118. The missions were on average longer than those of the other two cities due to the expansiveness of the southern California metropolitan area. Many of the Los Angeles missions also overflew mountains which acted as geographic barriers that increased the ground transportation distance compared to the line-of-sight distance for the missions.

Furthermore, seven of the 12 reference mission exhibited a congestion penalty of greater than 100%. The congestion penalty was the ratio of the average travel time during peak congestion periods to the average unimpeded travel time during free-flow conditions. A congestion penalty greater than 100% implies surface travel during the rush hour period required on average more than double the free flow travel time.

Table 43 and Fig. 119 summarize the 10 reference missions defined for the Boston city case. A majority of the routes exhibited congestion penalties around 100% indicating significant peak hour congestion on the roadways. In contrast to Los Angeles' mountains, many of the Boston reference missions connected communities that were geographically separated by bodies of water and also exhibited large surface travel distances compared to their line-of-sight distance.

The 10 reference missions developed for the Dallas city case are presented in Table 44 and Fig. 120. The Dallas-Fort Worth metropolitan area exhibited relatively few geographic barriers to travel compared to the other two regions. Therefore, the primary potential advantage of air mobility in this market was not to significantly shorten the distance of travel compared to ground modes, but rather to overfly routes with high congestion penalties.

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Table 42 Reference mission characteristics for the Los Angeles case study

Reference Mission	Ground Distance (mi)	Line-of-Sight Distance (mi)	Automobile Travel Time *Off-Peak* *(min)*	Automobile Travel Time *On-Peak* *(min)*	Congestion Penalty
Defined Missions					
1. Malibu to Century City	27.5	23.0	45	82	82%
2. San Bernardino to Glendale	44.0	39.6	52	117	125%
3. Antelope Valley to L.A. City Center	61.5	43.2	82	110	34%
4. San Diego to L.A. City Center	122.0	111.0	125	195	56%
5. LA City Center to Long Beach	26.5	20.8	35	77	120%
6. Beverly Hills Hotel to LAX	13.0	9.5	30	67	123%
7. Redondo Beach to Dodger Stadium	22.7	17.9	37	95	157%
8. Rancho Palos Verdes to Hospital	8.5	5.3	18	23	28%
9. San Marino to Palm Springs	116.0	99.5	125	185	48%
Randomly Generated Missions					
10. San Bernardino to Perris	26.0	18.8	34	70	106%
11. Arleta to Corona	71.0	60.2	92	190	107%
12. Altadena to Culver City	30.0	21.2	58	130	124%

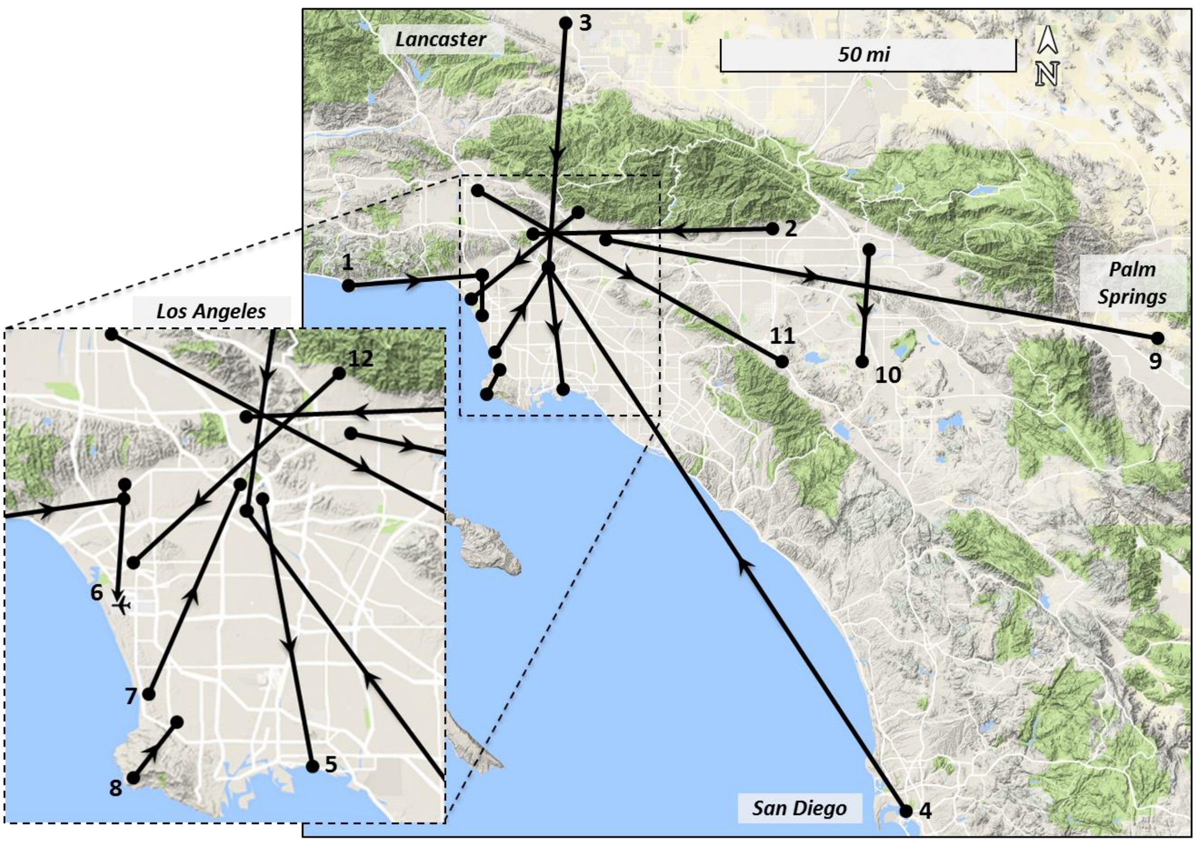

Fig. 118 Line-of-Sight flight trajectories for UAM reference missions in Los Angeles.
Map Data © 2017 Google, INEGI

Table 43 Reference mission characteristics for the Boston case study

Reference Mission	Ground Distance (mi)	Line-of-Sight Distance (mi)	Automobile Travel Time *Off-Peak* *(min)*	*On-Peak* *(min)*	Congestion Penalty
Defined Missions					
1. Providence to Boston Seaport	46.2	36.4	57	112	96%
2. Waban to Prudential Center	10.2	7.3	14	35	150%
3. Lexington to MIT	12.7	9.7	30	57	90%
4. Hull to Financial District	21.4	10.2	42	92	119%
5. Harvard to Martha's Vineyard	88.6	70.2	150	210	40%
6. Chestnut Hill to TD Garden	9.1	5.8	24	47	96%
7. Wellesley to Logan Airport	20.6	15.3	32	60	88%
8. Manchester-by-the-Sea to Harvard	33.5	22.9	45	87	93%
Randomly Generated Missions					
9. Dorchester to Cambridge	7.0	5.4	21	42	100%
10 West Roxbury to Belmont	10.1	7.7	28	47	68%

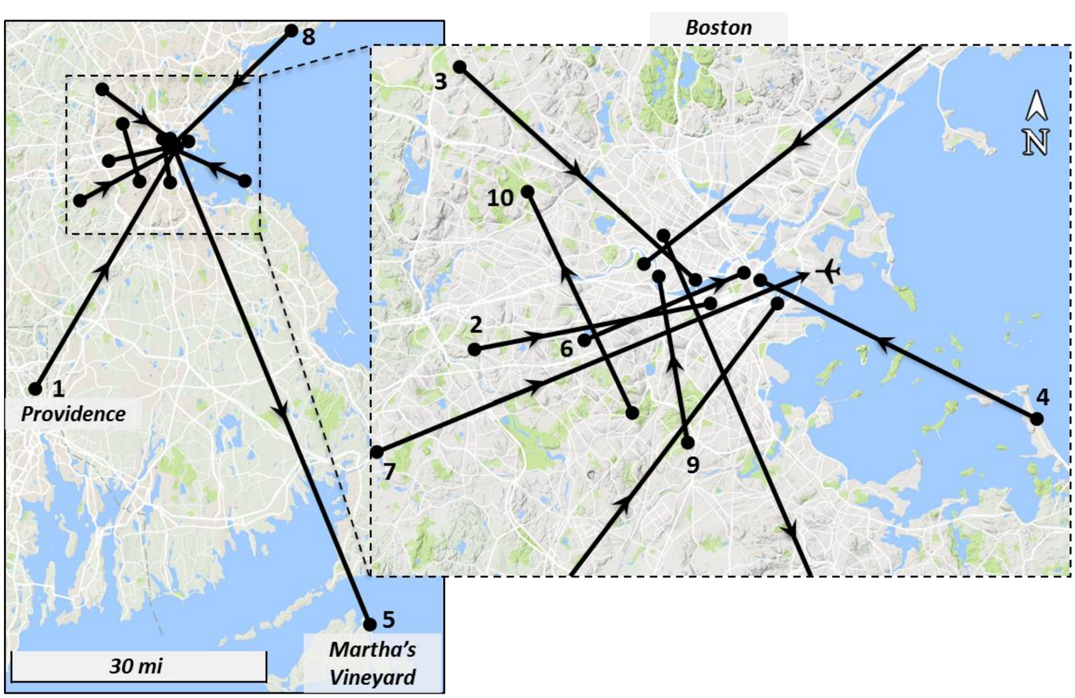

Fig. 119 Line-of-Sight flight trajectories for UAM reference missions in Boston.
Map Data © 2017 Google

Table 44 Reference mission characteristics for the Dallas case study

Reference Mission	Ground Distance (mi)	Line-of-Sight Distance (mi)	Automobile Travel Time *Off-Peak (min)*	Automobile Travel Time *On-Peak (min)*	Congestion Penalty
Defined Missions					
1. Frisco Square to American Airlines Center	26.6	25.0	31	58	87%
2. Union Station to McKinney	33.6	31.2	40	78	95%
3. Westlake to Dallas City Center	29.8	25.9	33	60	82%
4. Fort Worth City Center to Union Station	31.7	30.5	35	45	29%
5. DFW to Frisco Station	26.8	19.3	30	65	117%
6. Union Station to DFW	18.9	15.9	23	36	57%
7. Plano Station to Cowboys Stadium	38.6	29.5	40	65	63%
8. Meacham Airfield to Texas Motor Speedway	19.3	14.6	25	36	44%
Randomly Generated Missions					
9. Ferris to Irving	44.3	31.4	50	68	36%
10. Mansfield to Plano	53.0	40.1	63	100	59%

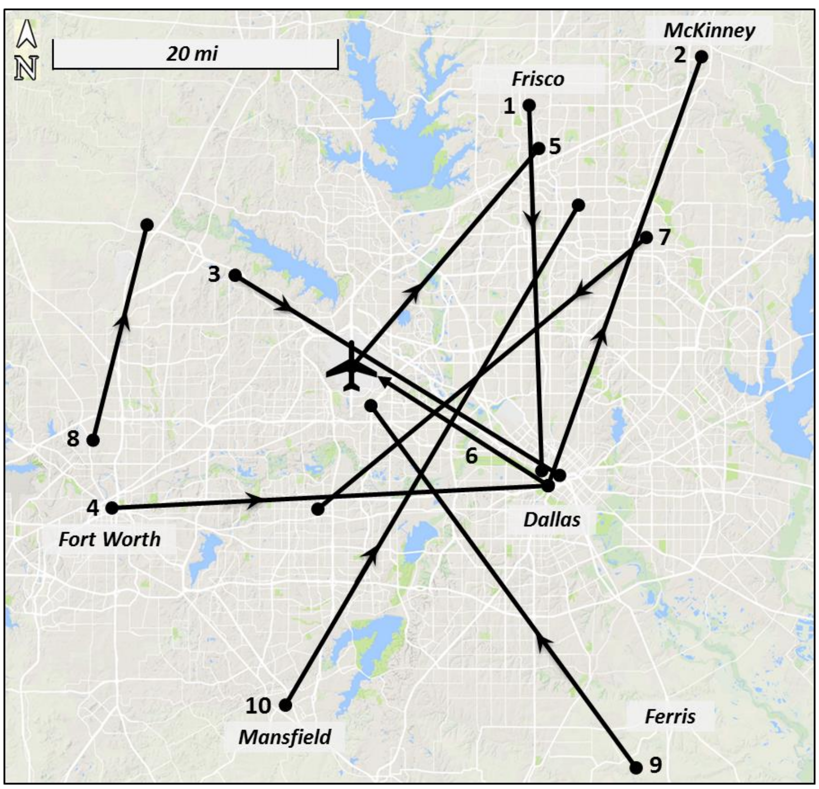

Fig. 120 Line-of-Sight flight trajectories for UAM reference missions in Dallas.
Map Data © 2017 Google

For each of the commuter references missions a surface transportation travel time profile was created using Google Maps™ mapping service travel time predictions. This information provided insight into the likely high-demand periods for a UAM service and provided an estimation of the surface congestion penalty.

An example of this travel time profile for a reference mission from the community of Hull to the financial district of Boston is provided in Fig. 121. A distinct bimodal pattern is evident indicating large congestion penalties during the morning and evening rush hour periods. Error bounds in Fig. 121 represent the high and low travel time estimates provided by the Google Maps™ mapping service while the travel time was the expected time. The average speed represents the total surface trip distance divided by the estimated travel time.

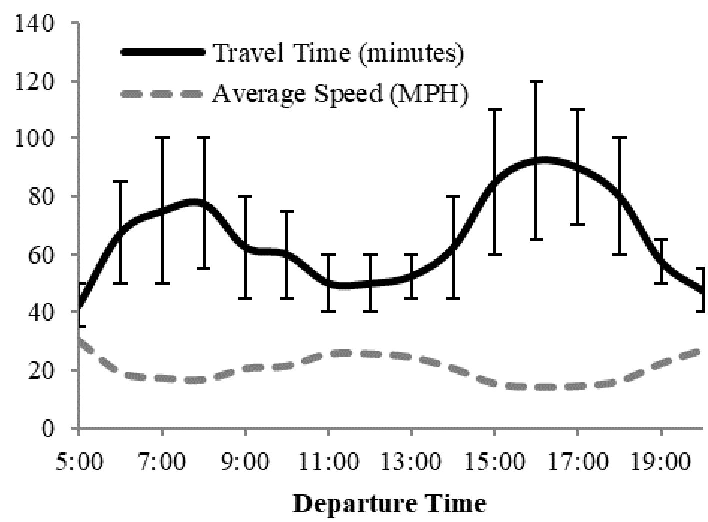

Fig. 121 Travel time and speed distributions for the Hull to Boston reference mission.

The Google Maps™ mapping service draws upon historic commuter and point-to-point travel information through GPS tracking. The maps use travel prediction algorithms that aggregate official speed limits, recommended speeds, likely speeds based on road type, historical average speed data (adjusted for time and day), actual travel time from users, and real-time traffic information [182]. The tool was assumed to be adequate to develop travel time profiles of sufficient accuracy for the case studies. Future studies may seek to develop more accurate travel time profiles and route mappings through the use of aggregated cell phone tracking data, such as shown in [183] and [184].

Through a sensitivity study that sampled each day of the week for multiple weeks throughout the year, it was determined that weekend traffic (inclusive of Friday) tended to be the most severe and often exhibited a different travel time profile than the standard weekday profile. Although each day of the week had a slightly different travel time profile, travel predictions for Tuesdays appeared to be roughly the mean of the standard weekday travel patterns. Therefore, Tuesday May 17, 2016 was selected as the representative day for this case study, and the reference mission travel time profiles were developed through the Google Maps™ mapping service travel predictions for this day. Future studies may create more comprehensive travel time profiles by considering an entire week and samples from multiple times of the year.

As an additional note, the Google Maps™ mapping service presented only aggregate data. While this was ideal to estimate daily commute references missions (albeit it did not capture variance in congestion due to road conditions such as major accidents or construction), it did not accurately represent the traffic that an individual may expect to encounter for point-to-point travel to non-recurring events such as sporting events. Therefore, the travel time profiles presented for the point-to-point reference missions that involve non-recurring events should be viewed as lower bound estimates of travel time as there was likely to be significant additional event congestion.

Finally, Table 45 provides the evaluation metric that was applied to determine if an operational challenge was present in each of the reference missions.

Table 45 Potential UAM operational challenges and reference mission evaluation metrics

Identified Operational Challenge	Reference Mission Evaluation Metric *(challenge exists in mission if metric evaluates positive)*
1. Weather restrictions	1. Do convective weather, instrument conditions, or sub-freezing conditions occur >10% of the year
2. Proximity of TOLAs to customer origin and destination	2. Does the duration of first/last mile surface transport require >30% of the nominal non-UAM driving travel time
3. TOLA integration with ground transportation networks	3. Does either TOLA lack onsite public transit or automobile parking
4. Customer physical access to TOLA	4. Is either TOLA in an area not accessible to the public
5. Access to controlled airspace	5. Does the flight use class B, C, D or special use airspace
6. Pilot communication with ATC	6. Does the flight use class B, C, D or special use airspace
7. Safety in high density flight areas	7. Does the flight use an SFRA, helicopter, or VFR route
8. Community acceptance of noise	8. Does flight occur at <500 ft in residential or tourist areas
9. Approach and departure clearways at TOLAs	9. Do the approach or departure clearways contain obstructions or interactions with a nearby airport
10. Safety of vertical flight segments	10. Is a vertical flight segment required (i.e., use of a helipad)
11. Availability of an alternate TOLA	11. Is there no secondary TOLA within 0.5 mi of each TOLA
12. Geographic balance of aircraft and pilots with customer demand	12. Is either TOLA >25 mi from the primary city center

Appendix F: Development of TOLA Capacity Envelope

In order to develop the capacity envelope of a given vertiport and parameter setting, the IP was solved numerous times to determine each feasible arrival and departure performance point on the envelope. A complicating factor was that initial testing found TOLA capacity envelopes differ from the envelopes of traditional airports in that the number of departures is not always a monotonically decreasing function of arrivals [95]. In other words, the capacity envelopes have distinct upper and lower surfaces that create a non-unique relation of arrivals to departures.

Considering this attribute of TOLA capacity envelopes, the approach taken in this analysis to define the entire capacity envelope was to repeatedly solve the IP with a sweep of scheduled arrivals from zero up to the maximum TOLA acceptance rate for the given time period. This sweep of scheduled arrivals was repeated with two objective functions for the IP. The first objective function awarded arrivals while penalizing departures to find the lower surface of the capacity envelope as displayed in blue in Fig. 122. The second objective function awarded both arrivals and departures in order to find the upper surface of the capacity envelope. Arrivals were always valued higher than departures in order to prevent an indeterminate solution where arrivals and departures could be traded.

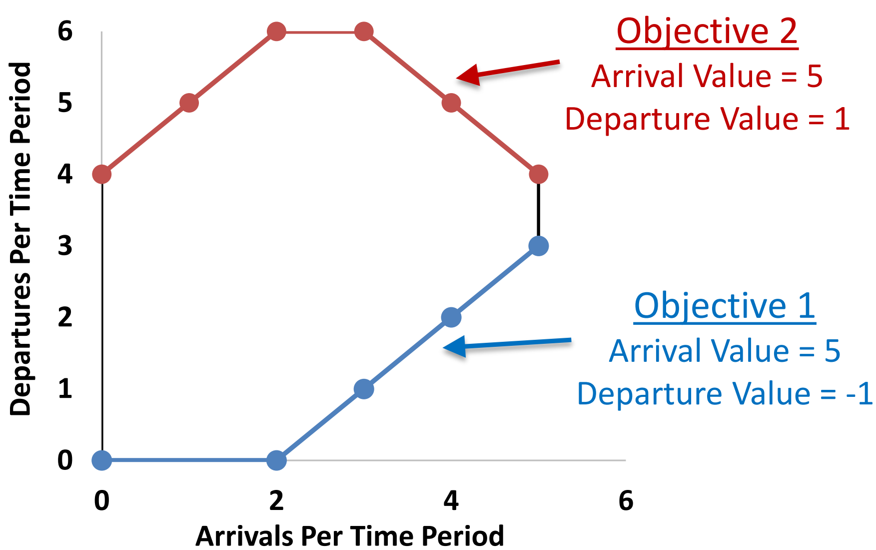

Fig. 122 The capacity envelope upper and lower surfaces were determined through separate IP objectives (i.e., different award schemes for arrivals and departures).