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# Evaluating the Interoperability of Urban Air Mobility Systems and Airports

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**Abstract**

This paper investigates how existing arrival and departure procedures can be directly used or adapted to enable high-volume instrument and visual urban air mobility (UAM) flight operations at major airports in the United States. Viable procedures are restricted to those that enable simultaneous and non-interfering UAM flights with conventional aircraft operations. Air traffic controller workload is proposed as the critical integration barrier to scale UAM operations in visual conditions whereas separation minima, especially for approach procedures, is proposed as the critical barrier in instrument conditions. A systems approach is taken to evaluate potential integration strategies for UAM in which the location of UAM runways or vertipads and flight procedures are presented in a topological framework. The benefits, challenges, and notional application of five integration schemes are discussed. Four promising procedures for UAM are introduced through case studies at three airports. Findings indicate that multiple procedures exist to support high-volume UAM integration at major airports under current regulations with additional controller staffing, especially if UAM aircraft exhibit helicopter-like performance.

The concept of urban air mobility (UAM) proposes to use one to nine passenger aircraft to provide on-demand or scheduled air transportation services within a metropolitan area and its surrounding suburban and rural communities. Catalyzed by a new generation of vertical takeoff and landing (VTOL) and short takeoff and landing (STOL) aircraft that leverage electric propulsion and increasing levels of autonomy, dozens of manufacturers anticipate beginning UAM services as soon as the mid-2020s and rapidly exceeding the scale of current or prior air taxi operations (*1*, *2*). Initial market studies indicate that shuttle services to, from, or in-between major airports represent a substantial portion of the near-term market for UAM (*3*). For example, a network of UAM feeder routes from remotely located terminals can expand an airport's passenger catchment area, increase its accessibility to far-flung or geographically disconnected communities, and provide faster airport access through overflight of surface congestion and ground obstacles.

This study considers air traffic control (ATC) as a critical barrier for the scaling of UAM operations (as opposed to terminal capacity or surface operations) at major airports. While prior air shuttle services to airports on the order of ten flights per hour have been demonstrated with helicopters and small aircraft in visual conditions, UAM proponents propose to operate at significantly higher traffic volumes and in instrument conditions (*2*, *4*, *5*). This study assesses the feasibility of high-volume, small-aircraft operations under both meteorological rule sets.

UAM integration proposals benefit from requiring minimal changes to conventional aircraft operations. Altering current procedures for large aircraft or repositioning existing runways will likely be prohibitively costly, time consuming, and politically intractable. Furthermore, most major airports currently experience capacity issues. Therefore, reducing conventional aircraft throughput to accommodate UAM aircraft will be unviable. Considering this, the objective of this study is to evaluate the siting of UAM takeoff and landing areas (TOLAs; i.e., runways, helipads, vertiports, etc.) and their flight procedures so as not to interfere with existing airport operations.

The approach taken in this study is to:

1. Identify aspects of ATC that will limit the scale of UAM airport operations in visual or instrument conditions;
2. Abstract the UAM airport integration design space in a topological framework;

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3. Identify unique airport integration schemes for UAM TOLAs and flight paths;
4. Evaluate each scheme's ability to support high-volume UAM operations in either meteorological condition and identify implications for UAM aircraft performance, ATC policy, or airport implementation; and
5. Display promising integration strategies through case studies at three airports with diverse characteristics.

Five distinct airport integration schemes for UAM were characterized in the topological framework. Converging and diverging operations were the most promising scheme for departures, for visual arrivals to crossing runways, and for STOL instrument arrivals. Converging and diverging procedures minimize separation requirements and additional controller workload. Widely spaced infrastructure with air or hover taxi connections to the terminals was the most promising scheme for instrument arrivals by VTOL UAM aircraft. Finally, closely spaced infrastructure may support visual arrivals by STOL or VTOL UAM aircraft, but the scheme has limited viability for operations under instrument flight rules (IFR).

## Background and Current Operations

Historic helicopter and small-aircraft operations at major airports provided initial insight into integration challenges and strategies for UAM. Efforts by de Havilland Aircraft in the 1960s found the development of all-weather approach and departure procedures that did not conflict with conventional flights to be the most demanding integration barrier (*6*). Flight demonstrations at the end of the decade by Eastern Airlines similarly concluded that the "non-interfering expansion of air traffic capacity" through independent procedures and airfield facilities was the primary operational restriction for air shuttle services (*7*).

Chicago Midway International and O'Hare International airports each supported approximately 50,000 helicopter operations in 1960, or an average of 135 flights per day (*8*). The FAA developed several novel strategies at the time to handle this volume of helicopter operations. These strategies included:

- Developing helicopter TOLAs that were located separately from the active runway(s),
- Designing helicopter routes that avoided conflicts 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 helicopters to fixed-wing aircraft.

Despite these strategies, high-volume helicopter operations at Midway and O'Hare were restricted to visual flight rules (VFR). No helicopter operator at the time was certified to fly under IFR, and the IFR separation minima were not compatible with the helicopter routes or TOLA locations.

Two decades later, Ransome Airlines achieved non-interfering VFR shuttle flights into major airports through new STOL aircraft, navigational systems, and steeper arrivals to inactive runway ends (i.e., "stub" runways). More recent work by NASA evaluated high-throughput helicopter route designs for airports and explored new air traffic controller communication strategies (*9*). The emergence of unmanned aircraft systems (UAS) also led to terminal airspace modeling in an effort to identify unused airspace in which these systems can operate non-interferingly (*10*).

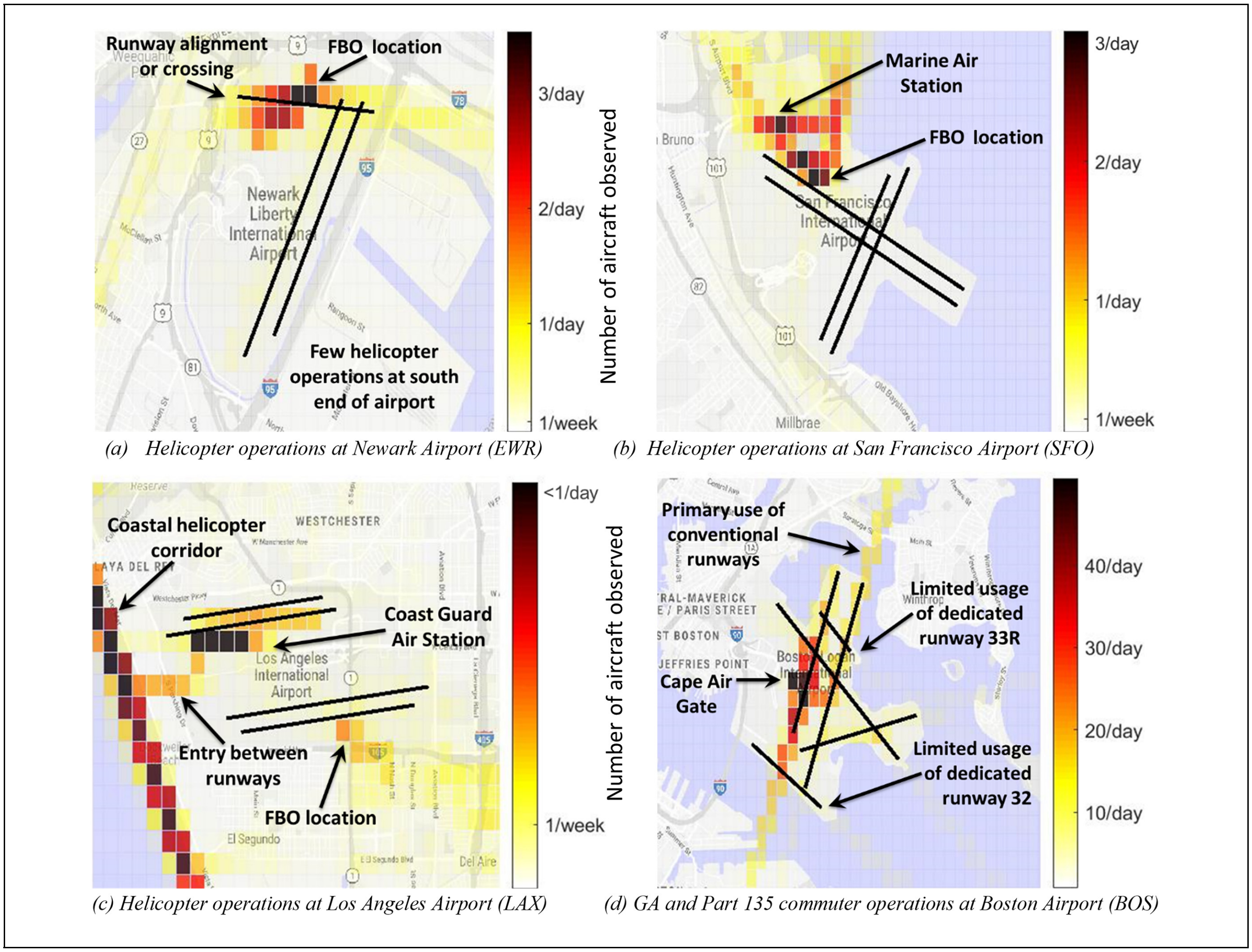
According to the FAA air traffic activity system, between 2016 and 2018 the 30 largest airports in the United States supported an average of 48 general aviation (GA) flights per day. Although this scale of operations is lower than that anticipated for UAM, the ATC strategies currently used to manage 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 these operators through methods introduced in Ref. (*11*).

Figure 1 displays heat maps of GA and helicopter flights below 1,000 ft above ground level (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; 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.

GA and commuter operations shared the conventional runways and procedures at nearly all airports. The exception was at BOS where two independent runways (33R and 32) exclusively support small aircraft. However, these runways are limited to VFR operations and a single wind configuration resulting in low utilization, as shown in Figure 1*d*.

As demonstrated at SFO and LAX in Figure 1, helicopters provide flexibility in approach and departure path design and the siting of TOLAs. Furthermore, ATC policies afford several special allowances to helicopters. These allowances are predicated on the unique performance characteristics of the helicopter including:

- Reduced approach speed, hovering, or both, which increases the time to conflict for a given




*(a) Helicopter operations at Newark Airport (EWR)* *(b) Helicopter operations at San Francisco Airport (SFO)*

*(c) Helicopter operations at Los Angeles Airport (LAX)* *(d) GA and Part 135 commuter operations at Boston Airport (BOS)*

**Figure 1.** Heat map of small-aircraft operations below 1,000 ft for 180 days of radar data in 2015 and 2016: (a) helicopters at EWR operate on or overtop runways; (b) helicopters at SFO operate without overflying runways; (c) helicopters at LAX either cross under runway procedures and enter airport between runways or access FBO located beyond the outermost runway; (d) small aircraft operations at BOS most frequently use conventional runways.
*Note*: FBO = fixed-base operator; GA = general aviation.

separation and reduces the minimum turn radius; this capability enables helicopters to operate with reduced separation minima and visibility requirements in many situations;

- Reduced ground roll, which increases margins for runway overrun or adjacent runway penetration, creates opportunities to limit wake vortex encounters, or provides greater flexibility for airfield infrastructure siting in both movement and non-movement areas; and
- Flexible glideslope and climb angles, which provide greater vertical separation between aircraft on adjacent procedures and enable approach or departure operations in proximity to surface obstacles.

VTOL (versus STOL) UAM aircraft are anticipated to exhibit performance characteristics similar to helicopters. However, it is unclear whether these new vehicles will ultimately be classified as helicopters and granted the same ATC allowances. Considering this uncertainty, this study evaluates UAM integration at airports for both fixed-wing aircraft and helicopter classifications.

## ATC Constraints for UAM Airport Interoperability

Similar to current aircraft operations, UAM throughput at major airports will be limited by runway capacity. Therefore, either the productivity of existing runways must be increased to support additional UAM flights or new TOLAs must be developed specifically for UAM.

The interoperability of UAM on existing runways or the siting of new TOLA infrastructure is primarily dependent on three attributes of ATC.

### Separation Minima

In terminal airspace, controllers must provide a specific distance, time, or height between an aircraft and other aircraft or obstacles. Longitudinal separation prescribes the aircraft following distance required to minimize wake vortex interactions, mid-air conflicts, or runway occupancy violations. Lateral separation minima limit how closely aircraft can simultaneously operate on procedures or runways. Longitudinal separation generally sets the throughput capacity of a given procedure or TOLA whereas lateral separation sets the runway and procedure siting.

Major airports operate within Class B airspace where controllers must ensure separation between all aircraft except between a VFR helicopter and any other helicopter. For all other aircraft, radar separation, visual separation, or non-radar separation must be applied.

VFR radar separation requires 1.5 nmi laterally or 500 ft vertically between aircraft. 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 nmi. VFR radar separation at Class B airports may be applied in weather conditions in which aircraft have visibility of at least 3 mi and can remain clear of clouds; Part 135 helicopters, however, only require visibility of 0.5 mi in the day or 1 mi at night. IFR radar separation may be applied in any weather and requires 3.0 nmi laterally or 1,000 ft vertically for all aircraft types.

If visual separation is applied, then pilots or controllers may use their own judgment to provide safe lateral and vertical separation; in this sense, there are no quantitative visual separation minima. Finally, non-radar separation uses time-based or heading-based methods to ensure aircraft separation.

### Controller Workload

ATC is currently a voice-based, human-centric activity in which controller workload is proportional to traffic volume, airspace complexity, and communications requirements, among other factors (*12–14*). Controllers may delay UAM access or egress at airports if their workload capacity is saturated. Controller workload is anticipated to be the attribute of ATC that will constrain UAM airport throughput under VFR.

The FAA does not use an explicit, quantitative method to specify the number of aircraft a single controller may support (*15*). Rather, controllers reach workload saturation when their cognitive load exceeds their personal comfort level to provide the required ATC services.

Initial human-in-the-loop experiments simulated for Dallas–Fort Worth Airport by NASA suggest that a local controller may be able to support between five and ten concurrent UAM arrivals alongside their current traffic load in visual conditions (*16*). To increase throughput further, towers may open additional controller positions. At GA airports, teams 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.

As an alternative or supplement to increasing controller staffing, ATC may reduce the amount of time a controller dedicates to an individual UAM flight. On average, controllers spend close to 30% of their time conveying routine clearances and information to pilots (*14*), and in terminal areas this may be as large as 50% (*16*). Approaches to reduce controller workload per UAM flight include developing visual procedures, enabling pilots to self-separate visually, and using data-link communications to minimize voice communication requirements. Strategies such as these are employed each year at the EAA AirVenture Oshkosh airshow and at the Silverstone Heliport during the British Grand Prix enabling both facilities to support multiple hundreds of GA operations an hour.

### Communication, Navigation, and Surveillance

Specific navigational aids, radar systems, and frequency spectra are used to support airport operations. Four communication, navigation and surveillance (CNS) capabilities were reviewed that may affect the scale of UAM airport operations. These are automatic dependent surveillance—broadcast (ADS-B), radio frequencies, traffic collision avoidance system (TCAS), and performance-based navigation (PBN).

Previous studies by MITRE and NASA determined that 1,400 or more ADS-B-equipped small, unmanned aircraft can be supported below 400 ft in a metropolitan area without frequency saturation if they use a low power setting (*17*, *18*). Although passenger carrying UAM operations will operate above 400 ft, the tradeoff between flight speed, aircraft density, and power setting provides flexibility to manage ADS-B frequency saturation and is not anticipated to restrict UAM operations.

High-volume UAM operations are likely to lead to radio frequency congestion. To address this, NASA demonstrated that UAM operations can reduce frequency of utilization in the near term through simplified route clearances (*16*), and that digital communication

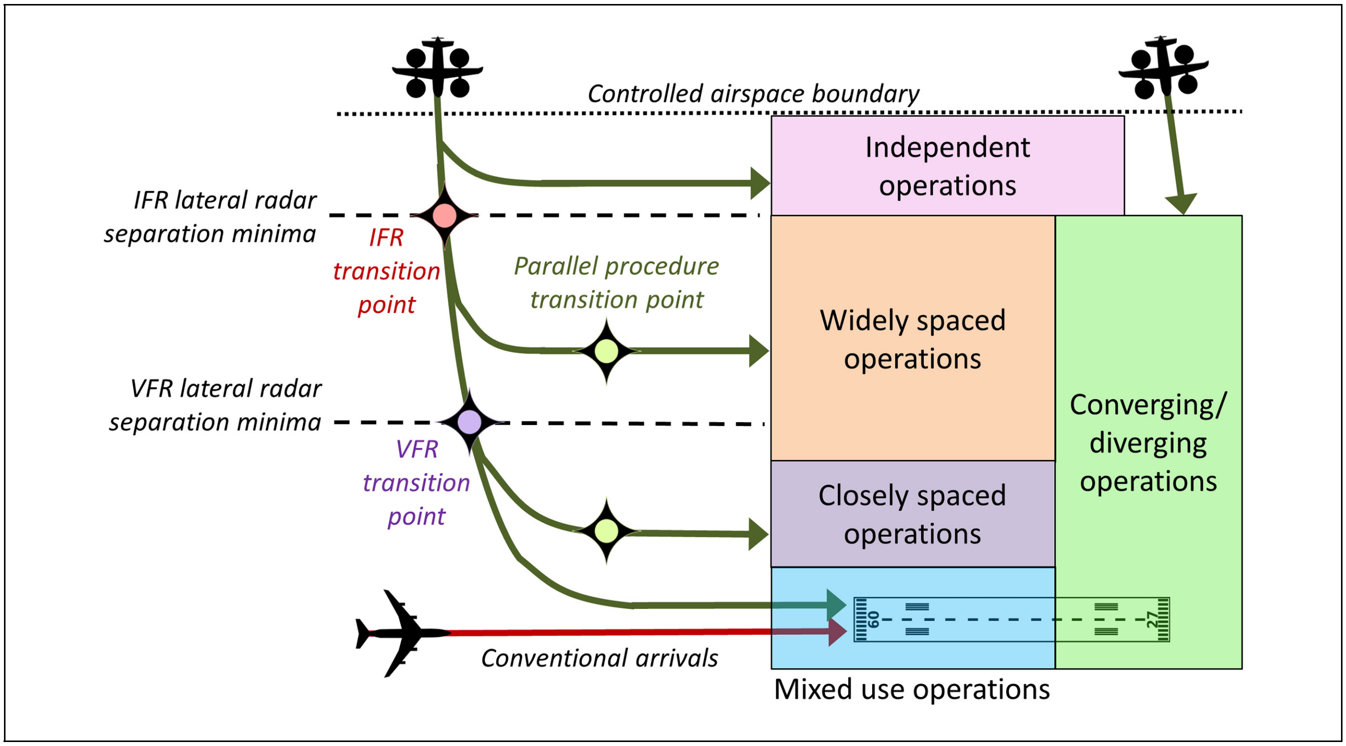



**Figure 2.** Topological framework of five operating schemes for UAM TOLAs located at airports.
*Note*: IFR= instrument flight rules; VFR = visual flight rules.

may be relied on rather than voice frequencies in the long term (*19*).

UAM approach and departure procedures to airports must not trigger TCAS alerts for conventional aircraft. This constraint will require UAM operations to remain below 1,000 ft or diverge from conventional aircraft during departures. UAM may avoid TCAS alerts during parallel arrivals by joining the glideslope within 2.2 nmi of the conventional runway's threshold. Finally, UAM operations below 360 ft AGL will never trigger a TCAS alert (*20*). These factors represent topological constraints for UAM integration.

Finally, PBN provides several opportunities to reduce separation requirements and relieve controller workload for UAM that are discussed in greater detail in the upcoming sections.

## Topological Framework of UAM ATC Airport Integration

To evaluate various means to integrate UAM services at a notional airport, a topological framework of an airport's runway infrastructure and flight procedures was developed. Five operating schemes were represented in the framework based on the distance and orientation of the UAM TOLA with respect to the airport's runways and flight procedures. As displayed in Figure 2, 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 basis for the parsing of the schemes was 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:

- Mixed use operations: 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 and the tempo of conventional operations are anticipated to set UAM runway throughput in this scheme.
- Closely spaced operations: 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. VFR UAM arrivals do not require additional controllers but may need to be sequenced with conventional aircraft for wake vortex separation requirements.

| | Conventional airport procedure | Minimum runway spacing (ft) | Minimum controllers | Restrictions |
|---|---|---|---|---|
| Parallel runways | Independent parallel approaches | 9,000 | 2 | none |
| | Simultaneous independent parallel approaches | 4,300 | 4 | none |
| | Simultaneous close parallel PRM approaches | 3,000 | 4 | PRM surveillance system required |
| | Simultaneous dependent parallel approaches | 2,500 | 2 | same approach speeds required |
| | Independent parallel departures | 2,500 | 1 | none |
| | High approach landing system | 1,640 | 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 | none |
| Non-parallel | Simultaneous converging instrument approaches | non-overlapping | 2 | restrictive design limitations |
| | Land and hold short operations | overlapping | 1 | not authorized in IMC |
| | Dependent converging instrument approaches | overlapping | 1 | wake vortex dependent |
| | Independent diverging departures | non-overlapping | 1 | none |

| | | | |
|---|---|---|---|
| Widely spaced operations | Closely spaced operations | Mixed use operations | Converging/diverging operations |

**Figure 3.** Overview of existing approach and departure procedures.
*Note*: PRM = Precision runway monitor surveillance system; IMC = Instrument meteorological conditions.

- 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 and 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.
- Converging operations, diverging operations, or both: 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 Figure 2 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, a controller must sequence the flight to ensure temporal separation, the aircraft must be established on a required navigation performance (RNP) approach procedure, or another type of separation (i.e., special VFR, 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.

Figure 3 summarizes approach and departure procedures currently used at airports. Each procedure sets different requirements for minimum runway spacing, workload, equipage, and aircraft performance as displayed. The procedures in Figure 3 are color-coded to match their underlying operating scheme from Figure 2. These procedures were used as a starting point to identify strategies for UAM integration near airports for each operating scheme.

## Strategies to Support UAM Airport Integration

This section discusses the feasibility of supporting UAM operations to TOLAs at or near airports in each of the five operating schemes presented in Figure 2. Specific technologies or policies that enable or enhance the throughput performance of the schemes are identified.

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

Although this scheme is a natural starting point for UAM integration at airports because it does not require new infrastructure investments, the mixing of UAM and conventional operations presents several challenges including:

- Proximity of UAM flights to wake vortices generated by large aircraft,
- UAM throughput limited by conventional aircraft operating tempo,
- Interaction of UAM and conventional aircraft on shared taxiways and runways, and
- Heterogeneous aircraft performance (approach speed, ground roll, etc.).

Despite these limitations, UAM aircraft operating under VFR, especially if certified as helicopters, may use visual separation to manage wake vortex separation requirements and operate in-between conventional operations. Visual UAM departures can occur behind a conventional departure without wake vortex requirements before the next conventional departure is authorized, and visual UAM arrivals can slot in-between conventional arrivals once they have passed the landing zone, stopped short, or turned off the runway. However, IFR UAM operations are not possible through this scheme without reducing conventional aircraft throughput as wake vortex requirements cannot be relieved through visual separation.

### *Operating Scheme 2: Closely Spaced Operations*

Compared with shared-runway operations, the use of separate UAM TOLAs can increase throughput by enabling simultaneous UAM and conventional operations. However, simultaneous closely spaced flights incur additional controller workload, operational restrictions, and CNS requirements, especially for IFR flights.

*VFR.* Closely spaced UAM VFR arrivals require lateral separation of 700–2,500 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 conventional operations.

Closely spaced departure operations are more restrictive than arrivals from a throughput perspective. UAM aircraft may be required to wait multiple minutes behind conventional aircraft departures on runways that are spaced less than 2,500 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 (e.g., ramp, apron, parking garage roof).

*IFR.* Closely spaced IFR operations occur at TOLAs separated by less than 9,000 ft but more than 700 ft from one another or a conventional runway. Multiple current procedures that support closely spaced IFR operations are highlighted in purple in Figure 3.

Simultaneous arrivals with separation of less than 2,500 ft 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 are 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 3,000–9,000 ft do not require precise sequencing of aircraft or similar approach speeds. However, controller workload remains a potential scaling constraint as three additional controllers are required to support a single new UAM TOLA of this scheme. An advanced radar may also be required as indicated in Figure 3.

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 3,000 ft.

*TOLA Siting and Terminal Access.* Closely spaced VFR operations may enable rapid UAM terminal access as the operations may occur from non-movement areas or even from helipads co-located with terminals. IFR operations, however, may be challenging to site at airports, especially for concepts in which separation is greater than

3,000 ft. Strategies to reduce taxi time or passenger transfer times between distant UAM TOLAs and commercial terminals are discussed under Scheme 3.

## Operating Scheme 3: Widely Spaced Operations

Widely spaced infrastructure simplifies the challenge of UAM integration from an ATC standpoint, especially during instrument conditions. The widely spaced configuration relieves requirements to sequence UAM with conventional flights, to staff additional controllers for trajectory conformance monitoring, or to use advanced radar systems. However, the widely spaced configuration negatively affects the siting flexibility of UAM. Furthermore, widely spaced UAM TOLAs exacerbate the challenge of rapidly connecting UAM passengers to the commercial terminals.

*VFR.* Widely spaced VFR operations must be separated from conventional runways by at least 2,500 ft. No wake vortex separation requirements apply to these operations for either arrivals or departures. Because UAM aircraft pass the VFR transition point on arrival, visual separation must be applied. One tower controller is authorized to handle VFR UAM arrivals simultaneously with conventional aircraft arrivals.

*IFR.* Widely spaced IFR arrivals must be separated by at least 9,000 ft from conventional flights. IFR departures, however, only require 2,500 ft of separation. If UAM aircraft use EoR procedures, then no sequencing or separation services are required from controllers minimizing their workload.

*TOLA Siting and Terminal Access.* The siting of UAM TOLAs and their accessibility to the terminals is the critical implementation challenge for widely spaced infrastructure. Terminal accessibility is defined as 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, the use of people movers, buses, or on-demand car services to enable rapid passenger transfers from remote gates, aprons, or terminals is a common practice at many airports. 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 for concepts that are electrically powered. Second, air taxiing must occur within the lateral bounds of the airport boundary.

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 then proceeds to a gate. A PinS approach may support widely spaced IFR arrivals to TOLAs separated by the VFR separation minima.

Figure 4*a* displays concepts for widely spaced IFR arrivals with air taxiway or surface transfer connections to the terminal. Figure 4*b* displays the PinS concept for widely spaced IFR arrivals.

## 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.

The disadvantage of independent operations is the large separation required between TOLAs or between a TOLA and the airport. Providing 3 nmi between TOLAs for IFR operations will preclude multiple facilities from simultaneously serving a metropolitan area. Furthermore, a 3 nmi 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. This scheme is not considered further.

## Operating Scheme 5: Converging or Intersecting Operations

The final 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 several 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 under VFR and IFR. Third, converging arrivals do not require additional controllers to monitor trajectory conformance.

Despite these advantages, the implementation of IFR converging arrivals may be restricted at some airports because of procedure design requirements.

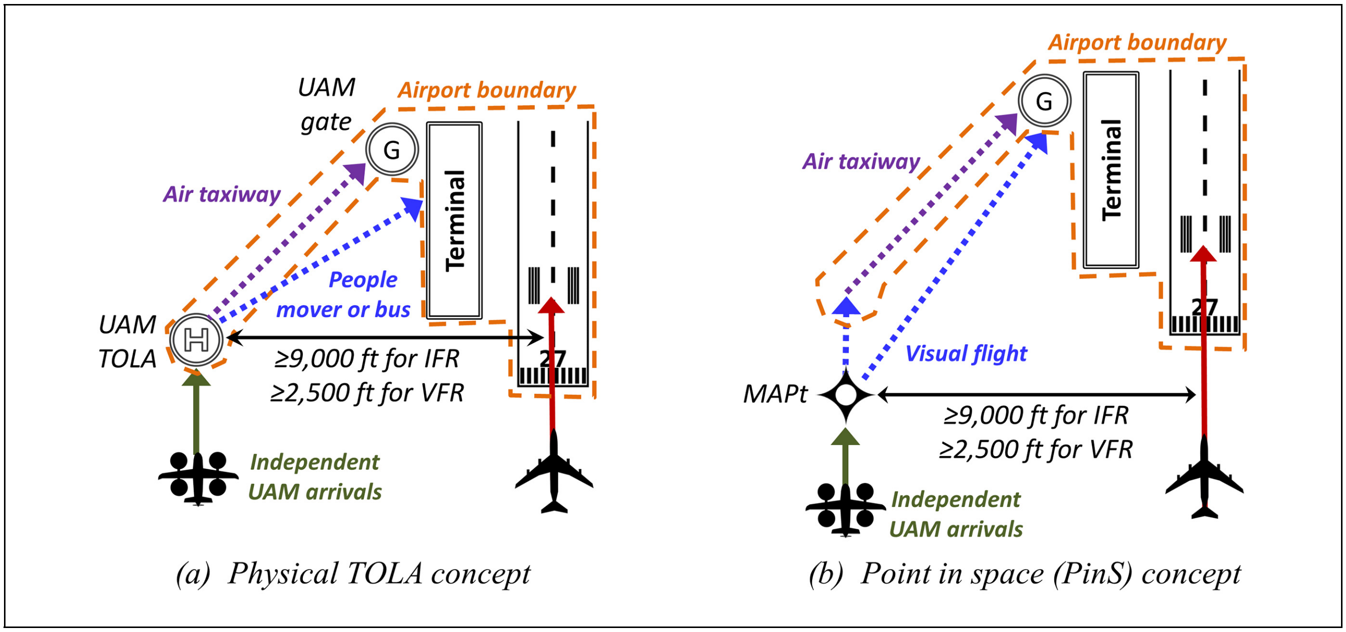



**Figure 4.** Concepts to provide increased terminal accessibility for widely spaced urban air mobility (UAM) arrivals under instrument flight rules (IFR). (a) UAM aircraft arrives to a physical takeoff and landing area (TOLA) before proceeding to the gate or offloading passengers; (b) UAM aircraft arrives to missed approach point (MAPt) and proceeds to gate via visual flight or air taxiing.
*Note*: VFR = visual flight rules.

*VFR.* 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 that it may enable UAM landings on existing crosswind runways without affecting conventional aircraft throughput or requiring independent controllers. Ransome Airways used the LAHSO concept in the 1980s to operate DC-7 commuter flights at Washington National Airport without sequencing into the standard arrival flow pattern. Figure 5*a* displays a notional LAHSO operation for UAM.

VFR or IFR UAM departures that diverge from the conventional runways by at least 15° are exempt from wake vortex requirements.

*IFR.* Simultaneous converging instrument approaches (SCIA) enable UAM aircraft to land on a converging but non-intersecting runway without requiring coordination with conventional flights. 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 aircraft 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 procedure at least 3.0 nmi from the other. This requirement limits either the approach radial, decision height, or touchdown location that UAM aircraft can use. However, prior 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 (*21*). Furthermore, UAM aircraft with lower approach speeds, hover capability, or shallower glides slopes may enable closer MAPt spacing at an equivalent level of safety. Figure 5*b* displays a notional SCIA for UAM operations.

*TOLA Siting and Terminal Access.* A converging and diverging scheme 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 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.

## Airport Case Studies of Promising Airport Integration Strategies

SFO, ATL, and BOS international airports were evaluated as case studies for UAM integration. These airports

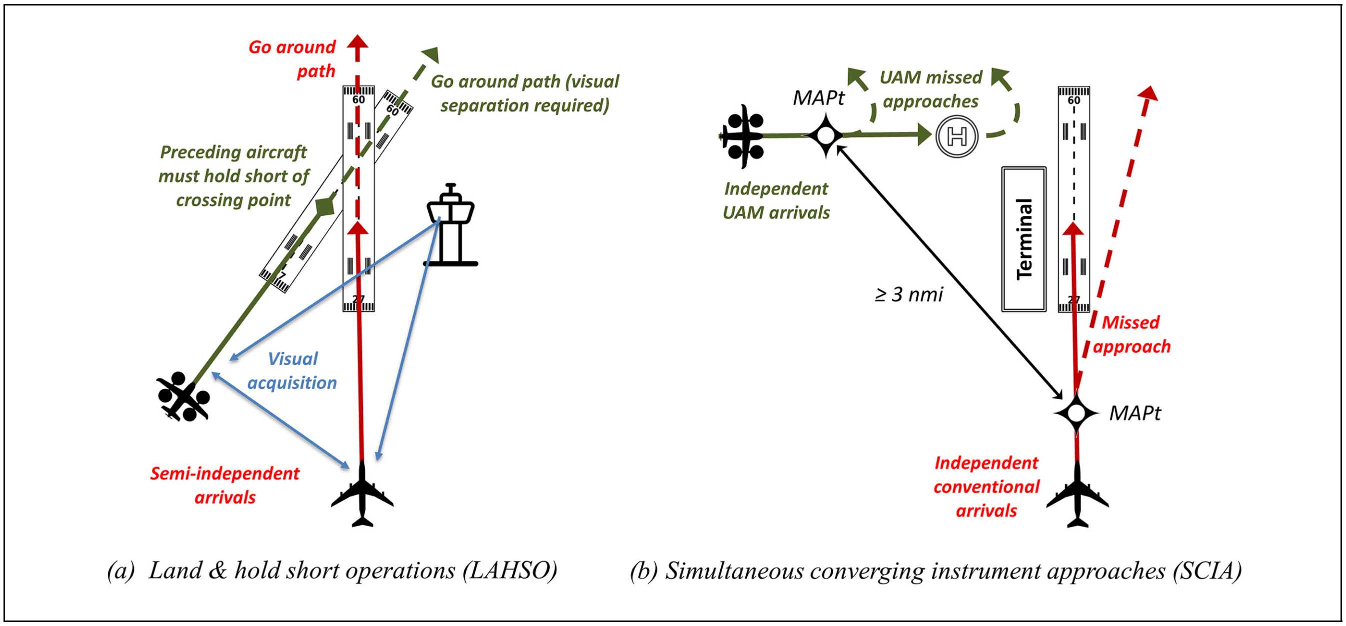



**Figure 5.** Two converging arrival concepts for urban air mobility (UAM) airport integration. (a) LAHSO can support simultaneous UAM and conventional arrivals on crossing runways under visual flight rules; (b) SCIA could potentially support simultaenous UAM and conventional arrivals on converging infrastructure under instrument flight rules.
*Note:* MAPt = missed approach point.

exhibit different contextual factors anticipated to influence UAM integration, including their runway configuration, the proximity of flight obstructions to the airport, and the type of approach procedures used by conventional aircraft.

For the case studies, four airport integration strategies that show promise under different weather scenarios are considered. These strategies are from operating Schemes 3 and 5 and include:

- 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. UAM operations are considered independent from an ATC standpoint and there is no minimum separation distance between UAM TOLAs supporting diverging departures and other runways or TOLAs.
- Converging arrivals: For VFR operations, converging arrivals have no minimum separation to conventional runways. LAHSO supports UAM arrivals to existing crossing runways, and converging VFR arrivals may be conducted to a new UAM TOLA as long as aircraft flight paths do not overlap. For IFR operations, SCIA may enable arrivals to new UAM TOLAs if relief to the 3.0 nmi MAPt separation policy is authorized.
- Widely spaced IFR PinS arrivals: UAM aircraft may conduct simultaneous and independent IFR arrivals through a PinS that is widely spaced from the airport (i.e., >9,000 ft from conventional operations). Weather permitting, the UAM flight may transition 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 are conducted to TOLAs spaced 2,500 ft from conventional runways followed by an air taxi segment to a gate located near the terminal.

### Identifying Airspace Currently Used by Conventional Flights

A core assumption of the study is that UAM flights will be required to interoperate with airports in a manner that is minimally interfering with conventional flights. To determine airspace used by conventional aircraft, radar tracking data were evaluated from 2015 and 2016. “Containment boundaries” that describe the lateral and vertical extent of airspace used by 99.5% of transport and regional jet aircraft were developed from the trajectory data through the approach introduced in Ref. (*11*).

### UAM Operations in Proximity to ATL

Figure 6 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 Figure 6, and the airport’s runways are shown with black bars.

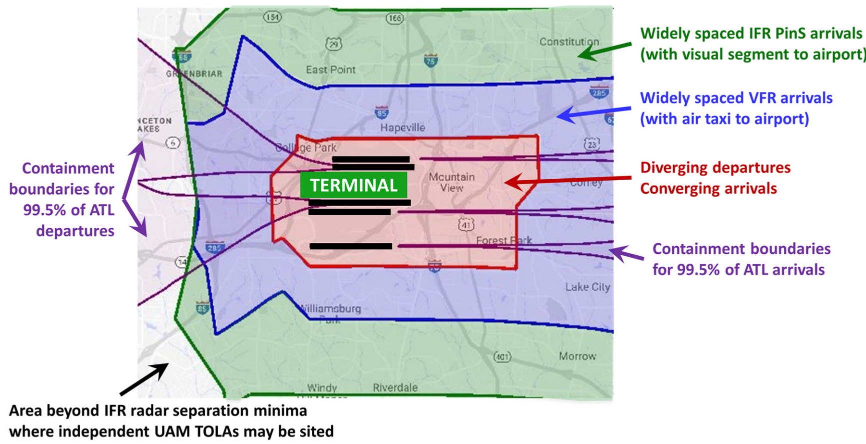



**Figure 6.** Airport integration strategies at ATL for a west flow pattern (64% frequency).
Note: ATL = Atlanta international airport; IFR = instrument flight rules; VFR = visual flight rules; UAM = urban air mobility; TOLA = takeoff and landing area; PinS = point in space.

IFR or VFR UAM flights may conduct converging and diverging operations to TOLAs located within or beyond the red region of Figure 6. The ATL terminal is imbedded between parallel runways preventing converging or diverging UAM operations directly to the terminal. UAM aircraft cannot 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) will be required from UAM TOLAs located beyond the outermost runways. ATL's inner runways are not spaced sufficiently to allow a UAM widely spaced VFR arrival to fly between them to the terminal.

Widely spaced VFR arrivals to the blue region of Figure 6 are similarly limited by the imbedded nature of the ATL terminal. Widely spaced TOLAs sited north or south of the airport will require subsequent taxiing over the runway or a ground transportation segment to the terminal.

PinS arrivals to the green region of Figure 6 may support IFR UAM arrivals with reduced complexity compared with converging IFR arrivals. PinS operations north of the airport will require a 2.5 mi visual flight segment to the terminal. The visual segment can follow either I-75 or I-85 from the MAPt to the airport. (Note that UAM aircraft cannot continue directly to the terminal under visual flight as wake vortex separation requirements will not be met between the runways; rather, air taxiing or ground transportation will be required.)

Figure 7 displays how a TOLA located 2,500 ft north of ATL's north-most runway can support either widely spaced VFR arrivals or converging/diverging operations. This TOLA is sited within the current airport boundary and an air taxi segment can be used, with sequencing, to cross the runways and access the ATL terminal.

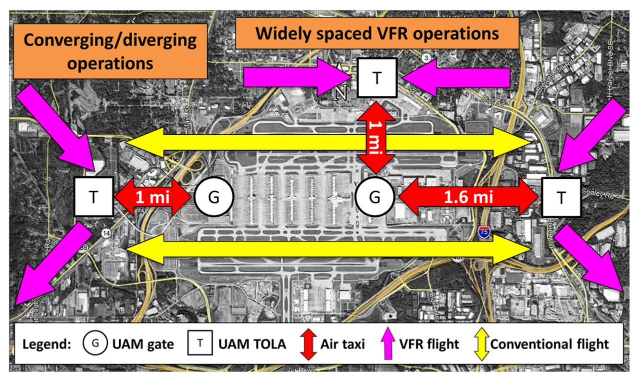
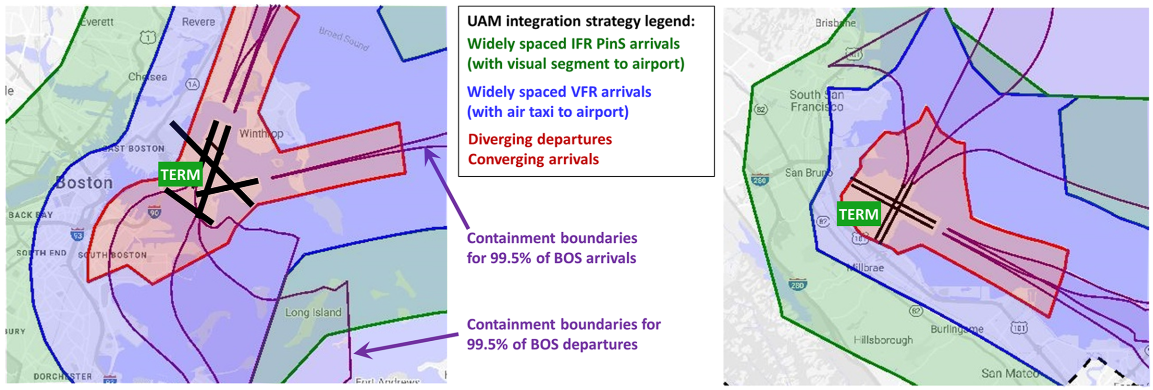



**Figure 7.** Notional converging/diverging and widely spaced operations for UAM integration at ATL in either east or west flow patterns. Map © 2019 Google.
*Note:* VFR = visual flight rules; UAM = urban air mobility; TOLA = takeoff and landing area.

Alternatively, converging/diverging operations at a TOLA located 1 mi 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 Figure 7, UAM aircraft arriving to a TOLA west of the airport may air taxi the remaining mile to a gate co-located at the terminal; the air taxi segment is not subject to separation minima. If ATL shifts to an east flow pattern, UAM can shift VFR arrivals to a TOLA located approximately 1.6 mi east of the airport. As a potential limitation, neither of these TOLAs would




(a) BOS southwest flow – 28% frequency (b) SFO west flow – 83% frequency

**Figure 8.** Urban air mobility (UAM) integration case studies for Boston (BOS) and San Francisco (SFO) international airports in one flow pattern. (a) regions for each UAM integration strategy at BOS; (b) regions for each UAM integration strategy at SFO.
*Note:* IFR = instrument flight rules; VFR = visual flight rules; TERM = airport terminal location; PinS = point in space.

be on airport property and air taxiing is not authorized beyond airport property.

### UAM Operations in Proximity to SFO and BOS

Figure 8 displays the UAM integration opportunities at SFO and BOS in commonly used runway flow patterns.

BOS provides several advantages over ATL in relation to 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 Figure 8, runway 15R (positioned directly north of the terminal) can support widely spaced VFR arrivals in the pictured southwest flow pattern. ATL did not have this opportunity because of its parallel runway configuration.

Second, the BOS terminal is not imbedded between parallel runways as in the case at ATL. Therefore, converging or diverging UAM operations can potentially use a TOLA co-located with the terminal for some flow patterns (such as the southwest flow pattern displayed in Figure 8).

Third, visual flight and air taxi segments from remote TOLA locations may provide easier 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 0.5 mi northeast of the terminal. IFR PinS arrivals may be flown to a MAPt over water approximately 1.5 mi from the terminal. Both integration strategies will require an air taxi or visual flight segment to connect to the terminal. Neither of the integration strategies will require UAM flight beneath conventional aircraft operations (including missed approaches) during a southwest flow pattern.

SFO operates in a west flow pattern 83% of the time. In the west flow pattern, conventional 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 interacting 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. Missed approach interactions are an area of future research.

The SFO terminal is 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 Figure 8 may also support UAM access to TOLAs in proximity to the terminal.

For IFR operations, a PinS to a TOLA due west of the airport in the green region of Figure 8 followed by a visual segment to the airport will overfly several densely populated residential communities. To mask noise and reduce population overflight, a PinS can 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 can follow Highway 101 to reach the terminal.

## Conclusion

Low-volume UAM airport shuttle flights may be supported on existing airfield infrastructure with procedures similar to current GA or helicopter operations. However, high-volume UAM operations at airports necessitate the development of UAM-specific procedures and TOLAs that support simultaneous and non-interfering small-aircraft operations alongside conventional flights.

Five distinct operating schemes were identified and evaluated for UAM integration at airports. From these general topological schemes, one departure strategy and three arrival strategies were identified as most promising, namely:

1. Converging arrivals,
2. Widely spaced VFR arrivals with an air taxi segment,
3. Widely spaced IFR arrivals on a PinS procedure, and
4. Diverging departures.

Each strategy uses either existing flight procedures or modifications of existing flight procedures based on anticipated flight capabilities of UAM aircraft. Furthermore, the strategies were anticipated to minimize requirements for additional controller staffing or new CNS technologies to simplify implementation.

Key findings of this study are as follows:

1. UAM airport integration under VFR is constrained by wake vortex separation requirements and controller workload. Diverging departures from shared or separate runways mitigate the wake vortex restrictions. LAHSO can enable the use of existing, crosswind runways for independent VFR UAM operations. Alternatively, widely spaced VFR arrivals with an air taxi segment can enable flexible TOLA siting and minimize controller workload.
2. UAM airport integration under IFR is most constrained by separation minima on final approach. PinS approaches or SCIA are promising strategies to enable IFR arrivals to new airport TOLAs. However, PinS approaches require weather conditions that permit visual flight following the MAPt and SCIA is limited for application to UAM by current design requirements.
3. UAM aircraft classification as a helicopter (as opposed to a fixed-wing aircraft) 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 mi when classified as a helicopter, but a 3.0 mi minimum when classified as a fixed-wing aircraft. Second, only helicopters are authorized to air taxi or conduct PinS approaches. Finally, helicopters benefit from wake vortex separation minima reductions because of their unique performance capabilities and may be relieved from the restrictive SCIA design requirement.
4. Airports with terminals that are imbedded between runways reduce the opportunity for simultaneous and non-interfering UAM services to the terminal, especially in instrument conditions.
5. The EoR procedure is an enabling navigational capability that reduces controller workload and simplifies UAM IFR integration near airports.

Considering these findings, there are numerous potential pathways to achieve high-throughput UAM interoperability at major airports. Future work may simulate throughput and evaluate airport-specific implementations of the concepts presented in this paper. Future work in the form of a safety risk management process should also evaluate each strategy, especially the SCIA procedure with reduced MAPt separation for UAM aircraft.

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## Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: P. Vascik, J. Hansman; data collection: P. Vascik; analysis and interpretation of results: P. Vascik, J. Hansman; draft manuscript preparation: P. Vascik, J. Hansman. All authors reviewed the results and approved the final version of the manuscript.

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