SCALING CONSTRAINTS FOR URBAN AIR MOBILITY OPERATIONS: AIR TRAFFIC CONTROL, GROUND INFRASTRUCTURE, AND NOISE

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Scaling Constraints for Urban Air Mobility Operations: Air Traffic Control, Ground Infrastructure, and Noise

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The scalability of the current air traffic control system, the availability of aviation ground infrastructure, and the acceptability of aircraft noise to local communities have been identified as three key operational constraints that may limit the implementation or growth of Urban Air Mobility (UAM) systems. This paper identifies the primary mechanisms through which each constraint emerges to limit the number of UAM operations in an area (i.e. the scale of the service). Technical, ecosystem, or operational factors that influence each of the mechanisms are also identified. Interdependencies between the constraints are shown. Potential approaches to reduce constraint severity through adjustments to the mechanisms are introduced. Finally, an effort is made to characterize the severity of each operational constraint as a function of the density of UAM operations in a region of interest. To this end, a measure of severity is proposed for each constraint. This measure is used to notionally display how the severity of the constraint responds to UAM scaling, and to identify scenarios where efforts to relieve the constraint are most effective. The overall purpose of this paper is to provide an abstraction of the workings of the key UAM operational constraints so that researchers, developers, and practitioners may guide their efforts to mitigation pathways that are most likely to increase achievable UAM system scale.

I. Introduction

URBAN Air Mobility (UAM) refers to a set of vehicles and operational concepts proposed to provide on-demand or scheduled air transportation services within a metropolitan area to overcome increasing surface congestion. Proponents of UAM anticipate that advancements in electric aircraft, automation, and telecommunications driven by Unmanned Aircraft System (UAS) and automobile applications may enable novel Vertical Takeoff and Landing (VTOL) or ultra-Short Takeoff and Landing (uSTOL) aircraft to provide UAM services in the early 2020's. However, previous evaluation of potential UAM system operations in Los Angeles, Dallas, and Boston proposed that the scalability of existing air traffic control systems, the availability of aviation ground infrastructure, and the acceptance of UAM generated noise by local communities may constrain the implementation or scaling of UAM systems [1].

The ability of UAM aircraft to reliably access and conduct high density operations within controlled airspace constitutes an Air Traffic Control (ATC) constraint. Current ATC procedures are anticipated to be insufficient to handle a large number of new UAM aircraft as a result of air traffic controller workload limitations and the required separation minima. Similarly, the design of current airspace and flight routes potentially restricts UAM access to significant portions of the airspace above metropolitan areas. While limited-scale operations may be supported within the current ATC system through the same means charter and general aviation operations are today, the current system may ultimately place limits on the density a UAM system may operate at, the number of operations that may occur, or the locations and times at which operations may occur [2].

The availability of takeoff and landing infrastructure will constrain near-term UAM operations and the scaling of these systems. While the development of a limited set of high-capacity Takeoff and Landing Areas (TOLAs) for UAM aircraft in demand-rich areas may support initial implementation of services along specific routes and corridors, a significant development challenge exists if the service is to become available to a broad geographic area with high capacity. The lack of TOLA infrastructure has been shown to amplify aircraft staging, airspace congestion, and route capacity challenges [3].

Local communities have a variety of pathways through which to influence aviation operations they deem undesirable. Landowners may prohibit landings on their property and may file lawsuits against overflights that they

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perceive to degrade their quality of life and enjoyment of their property. Local governments may use zoning or building codes to limit or prohibit aviation infrastructure development or operations. Finally, congressional representatives may compel the FAA to change ATC procedures to reduce noise, as was the case in the Los Angeles Residential Helicopter Noise Relief Act of 2013 [4]. While community acceptance of UAM activities may be influenced by numerous factors including privacy, viewshed, pollution, safety, and equity, aircraft noise has dominated recent public discourse and action and represents a key constraint for UAM operations. However, the successful implementation of helicopter-based UAM operations in São Paulo, as well as the large private and charter helicopter operations in Moscow and Mumbai, indicate that local values and expectations significantly influence the actual severity of this constraint. U.S. and European communities may exhibit increased sensitivity to aircraft noise compared to other potential UAM markets.

These three operating constraints are of keen interest to researchers, potential operators, and transportation planners as they dictate if a UAM system may serve a few hundred customers per day or tens of thousands of customers per day. The contribution of this research is significant because it will support the estimation of achievable UAM system scale based upon local factors and the ecosystem of the city in which it is implemented. Furthermore, this work may support the evaluation of how potential design and operating decisions may increase system scale.

II. Approach

The purpose of this analysis was to rigorously characterize the mechanisms through which the noise, infrastructure, and ATC operational constraints manifest in a UAM system, and to evaluate how fundamental technical, ecosystem, or operational factors influence to what extent each constraint may limit UAM system scaling. The paper is organized into three major sections. Each section focuses on one of the three operational constraints. The approach displayed in Fig. 1 was applied within each section to evaluate the constraints.

For each constraint, available literature and previous operational experience with the constraint was collected. These sources were used to identify the set of technical, ecosystem, or operational factors that influence how the constraint emerges within an air transportation system. These factors are influenced by variation in UAM system design or operating environment and were expected to cause the constraint to emerge at different levels of system scale. Next, an influence mapping was developed that connected each factor to the constraint through one or more mechanisms. These mechanisms represent the pathways through which the factors influence the constraint.

Third, potential opportunities to reduce the severity of the constraint through each mechanism were discussed. These opportunities (which could be thought of as potential mitigation areas) were show to correspond to design decisions such as the adoption of specific new technologies or a change in the Concept of Operations (ConOps). Situations were identified where mitigation opportunities appeared to effectively eliminate the constraint for a given UAM scenario, as well as situations where the mitigation relieved the constraint through one mechanism, but the constraint remained active due to the impact of another mechanism.

Previous analysis presented by Ref. [5] proposed that the severity of each constraint, defined to be the degree to which the constraint hindered UAM operations, increased with the number of UAM operations projected to occur in a geographic area (i.e. the scale of the system). The fourth step of the analysis sought to more rigorously correlate the severity of the constraint to the scale of the UAM system by proposing a metric to represent the severity of each constraint. The notional metric and relation display how the severity of the constraint responds to scaling of the UAM system, and how the identified mitigation opportunities may affect this relation.

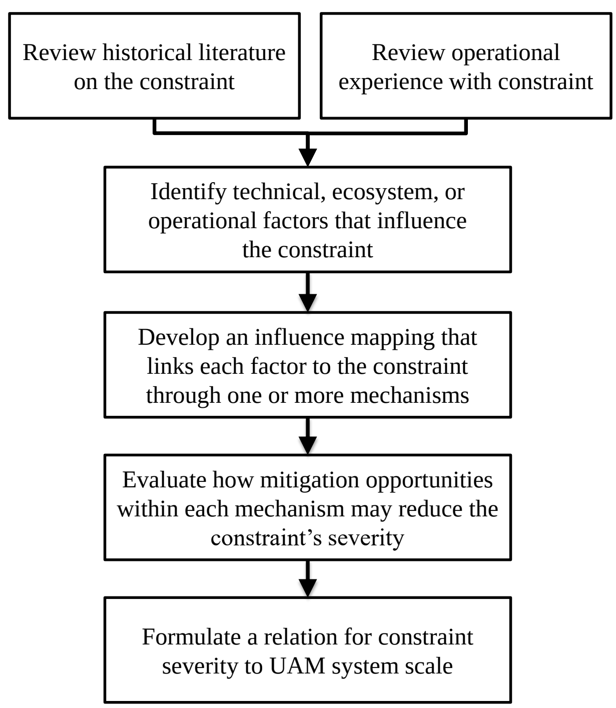

Fig. 1 Approach used to identify the influence factors for each constraint and predict the impact of the constraint on UAM system scaling.

III. Air Traffic Control Scalability

The potential emergence of large-scale UAM operations poses a number of challenges for safe and effective ATC. These challenges were shown in Refs. [2] & [6] to include managing a significantly increased number of total operations, supporting aircraft operations at far greater densities than those routinely seen today, providing services to aircraft at lower altitudes than most operations today, and interacting with pilots, automation, and aircraft that may have dramatically different training and performance capabilities than current flight crews. All four of these ATC challenges may limit how many aircraft can operate simultaneously in an airspace, and in what airspace they are allowed to operate. These ATC challenges are therefore said to represent ATC *capacity* constraints that limit the scalability of a UAM system.

Fig. 2 presents an abstraction of the airspace capacity management problem based upon Ref. [7]. Air traffic controllers seek to manage the number of operations within an airspace so that the volume of traffic within the airspace is less than the maximum practical capacity ATC can support. Controllers currently achieve this equilibrium either by increasing the capacity of an airspace (such as through adjustments to flight procedures or the number of controllers assigned to the airspace), or by limiting the traffic volume entering the airspace through Traffic Management Initiatives (TMI) or Temporary Flight Restrictions (TFR), among other options.

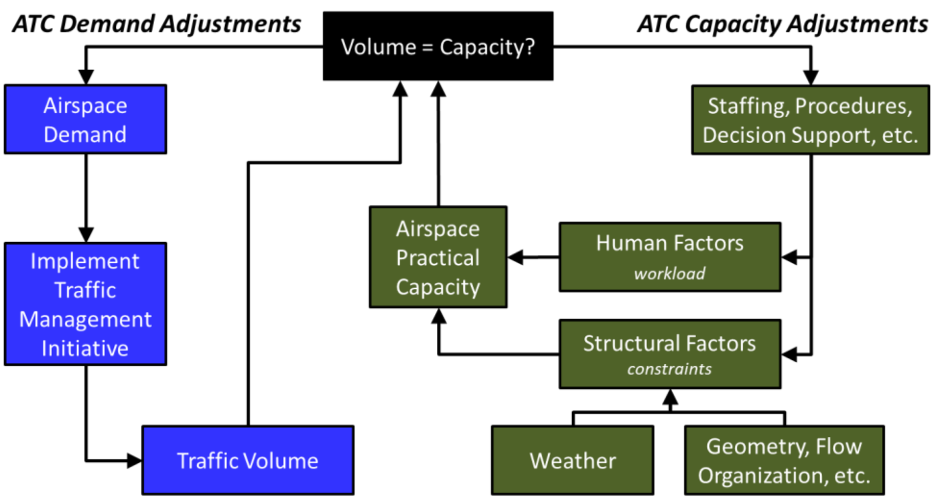

Fig. 2 Current approach by ATC to manage airspace capacity.

The introduction of a large volume of new UAM operations into airspace above metropolitan areas may overwhelm the current capabilities of ATC to increase airspace capacity. Controllers may therefore prohibit UAM aircraft from accessing Class B, C, or D controlled airspace, assign extensive ground or airborne delays that could make a UAM trip infeasible or unprofitable, or perhaps ration ATC services to prioritized users. Any of these responses by ATC to manage traffic volume effectively limit the number of UAM operations that can enter an airspace and the scalability of a UAM system [2].

A. Mechanism and Factor Influence Mapping

The "practical capacity" of an airspace sector is proposed as an appropriate metric to represent the ATC scalability constraint. Practical capacity is defined as the number of operations that can simultaneously be accommodated within an airspace sector while accruing no more than a specified amount of average delay. Practical capacity may therefore be thought of as the "carrying capacity" of a sector at a specific moment such that all flights are accommodated without undue delay. An airspace sector is a volume of airspace with designated boundaries that is managed by a dedicated controller or team of controllers.

While a rate metric for sector capacity (i.e. throughput) that describes the number of aircraft that could traverse a sector in a given period of time was considered as an alternative potential metric, it was not determined to be appropriate for UAM operations in low altitude airspace. The choice of practical capacity is consistent with the FAA's use of the Monitor Alert Parameter (MAP) which recommends maximum sector capacities based upon a variety of operational factors that affect controller workload [8]. Capacity is preferred to throughput because it is an instantaneous metric (i.e. does not require a reference time) and handles differences in aircraft flight trajectories and speeds through the consideration of delay.

The practical capacity of a sector represents the total number of all operations (UAM, commercial, UAS, general aviation, etc.) that could be accommodated in an airspace of interest at any one time with acceptable delay. It may therefore be considered to be the upper scalability limit of a UAM system before operations would be constrained by ATC in that airspace.

To assess what determines the capacity limit of a sector, air traffic control literature was reviewed and various influence factors were identified. Work by Ref. [9] suggested that controller workload, separation minima, traffic sequencing, and weather are major factors that cause variation in sector capacity. Refs. [7] & [10] determined that controller workload, airspace geometry, special use airspace, ATC ConOps (i.e. procedure and route design), weather, and Communication, Navigation, and Surveillance (CNS) capabilities determine sector capacity in terminal areas. Finally, Ref. [11] indicated that airspace capacity is driven by airspace geometry and controller workload factors.

A number of additional influence factors were also identified through discussions with helicopter operators and air traffic controllers. For example, due to the low altitude nature of UAM operations, airspace capacity may be influenced by community acceptance concerns that result in flight procedure curfews or overflight limits. Furthermore, pilot workload must be considered in addition to controller workload for high density operations, especially those occurring in Visual Flight Rule (VFR) conditions that rely upon pilot self-separation. Controller workload was also noted to be dependent upon the number and skill of the controllers staffed on an airspace, as well as the decision support tools and automation available to them.

A mapping of how each of these factors influence sector capacity is presented as Fig. 3. The figure displays how numerous influence factors (in orange) act through three mechanisms (in blue) to set the capacity of a sector. Two high-level influence pathways were also presented (in black). These pathways distinguish the mechanisms that affect sector capacity through structural changes in airspace operations from the mechanism that affects sector capacity through controller and pilot cognitive limitations. These two high-level influence pathways closely align with the "throughput rates" and "human factors" pathways suggested by Ref. [7].

The three indicated mechanisms directly influence sector capacity and represent the primary means through which a sector's capacity may be set. It is anticipated that sectors operating in different environments and scenarios may experience capacity limitations set by any one of the three constraints. The following sub-sections discuss situations where each mechanism is likely to drive a sector's capacity for UAM operations. Furthermore, potential opportunities to increase sector capacity through adjustments to each mechanism are discussed.

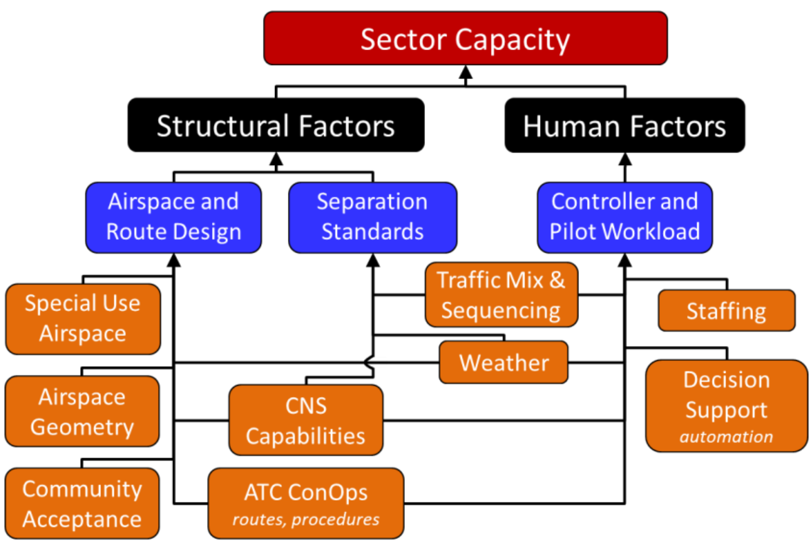

Fig. 3 Air traffic control sector capacity influence diagram.

1. Airspace and Route Design Mechanism

The geometry of a sector and the arrangement of flight operations within it in part determine the aircraft capacity of a sector. In the presence of inclement weather, particularly when convective in nature, the number of viable routes through the sector may be reduced [7]. Similarly, the creation of Special Use Airspace (SUA) may limit access to or fully close portions of a sector. Evaluation of METAR reports from July 1, 2016 to June 30, 2017 found that convective action may impact metropolitan airspace capacity in cities such as Atlanta for as much as 10% of the year. Temporary

Flight Restrictions (TFR), a type of SUA that excludes access for a majority of non-commercial carrier flights, were found to reduce airspace capacity above a majority of Boston for as many as 100 afternoons and evenings a year.

The CNS capabilities available to pilot and controller, the traffic flow ConOps deployed in the sector, and the influence that local communities may have upon airspace operations also influence sector capacity by controlling which routes, procedures, or airspace are available for aircraft operations. For example, the development of the Hudson River Special Flight Rules Area (SFRA) in New York changed the ConOps for flight in this airspace from active control by ATC to visually separated free flight. This resulted in an increase of the corridor's capacity (in visual conditions). Similarly, the implementation of Performance Based Navigation (PBN) has increased terminal area airspace capacity near airports by enabling new and more closely spaced approach and departure procedures with reduced containment boundaries [12]. However, recent years have also seen an increase in community acceptance issues regarding aircraft noise over metropolitan areas. This has caused a reconsideration of PBN routings in Charlotte, Boston, and Phoenix, among other cities.

Numerous opportunities exist to potentially relieve sector capacity limitations through the airspace and route design mechanism. One opportunity is to leverage PBN to enable closer spaced routes, or routes in closer proximity to traditional airport procedures. Similarly, the adjustment of airspace geometry and ConOps may enable more areas of pilot self-separation and corresponding capacity increases [3]. UAM aircraft could be authorized to operate in SUAs created for security purposes if they provide security screening to their customers. However, while this approach to access SUAs may reduce the ATC constraint, it may also negatively impact the ground infrastructure constraint by increasing required staff, terminal-space, and passenger processing time. The acceptance of UAM operations by local communities is an operational constraint in its own right and shall be discussed in Section V.

2. Separation Standard Mechanism

Around airports, especially in Instrument Meteorological Conditions (IMC), longitudinal and lateral separation standards (including wake vortex requirements) are often the primary mechanism through which sector capacity is limited. As presented in Table I, ATC is required to provide separation services dependent upon if aircraft are operating in weather conditions that enable Visual Flight Rule (VFR), Instrument Flight Rule (IFR), or Special VFR (SVFR) operations.

Table I Scenarios where U.S. ATC is required and not required to provide separation services.

Requirement	Scenario	Reference*
ATC is Required to Separate	IFR aircraft or helicopters in controlled airspace	-
	IFR aircraft and VFR aircraft or helicopters in Cass B & C airspace	7110.65W 7-8-3 & 7-9-4
	VFR aircraft and VFR aircraft or helicopters in Class B airspace	7110.65W 7-9-4
	SVFR operations and any other SVFR operation or IFR aircraft	7110.65W 7-5-3
ATC is not Required to Separate	VFR operations in Class G, E, D, or C airspace	-
	IFR operations and VFR operations in Class G, E, or D airspace	-
	VFR helicopters and VFR or IFR helicopters in any airspace	7110.65W 7-8-6 & 7-9-6

**FAA Joint Order 7110.65W as presented in Ref.* [13]

Operations that do not require ATC separation services must apply visual self-separation. This means pilots are required to "see and avoid" and pass "well clear" of other aircraft as described in Part 91.113 of Title 14 of the Code of Federal Regulations (CFR)[1]. For operations that require ATC separation services, controllers may apply a variety of separation methods and minima ranging from the same visual separation standards described above to highly restrictive IFR radar-based separation minima as displayed in Fig. 4. A review of potential UAM operations in San Francisco by NASA displayed how current IFR separation standards are incompatible with the flight densities required to support a UAM system [6].

A variety of potential approaches have been proposed to increase airspace capacity by reducing the required separation standards. The workings of these approaches may be described through the three factors that influence the separation standard mechanism in Fig. 3. One category of approaches seeks to control the mix of aircraft types entering

[1] All Title 14 references in this paper were from the electronic Code of Federal Regulations, http://www.ecfr.gov, retrieved from the version updated April 10, 2018.

an airspace (the traffic mix) and the order of these aircraft so as to minimize the required wake vortex separation and match aircraft speeds. Constrained Position Shifting (CPS) is an example of such an approach [14]. UAM may benefit in that the small aircraft proposed to provide the service will have similar wake vortex separation requirements. However, significant variability in the cruise speed and approach profiles of these aircraft may challenge effective sequencing and spacing.

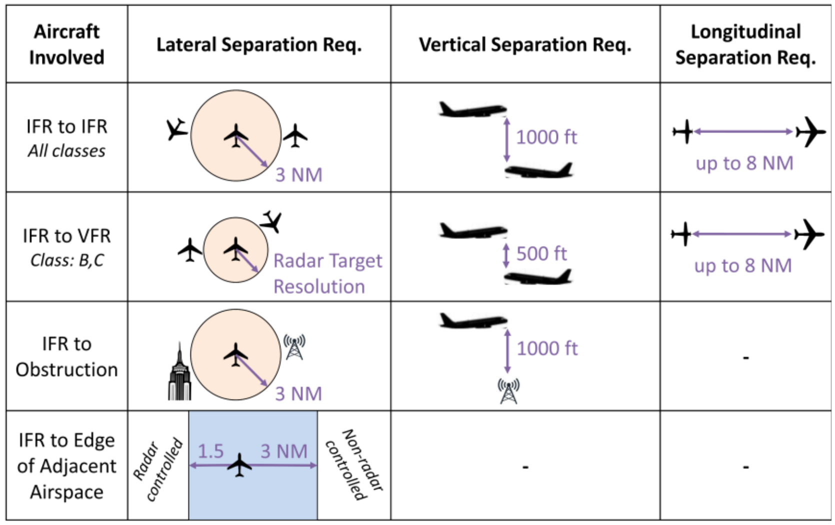

Fig. 4 U.S. ATC separation minima for terminal area operations.

A second set of potential approaches to reduce separation standards propose that advanced CNS in the form of vehicle to vehicle communication technologies, pilot automation, and new obstacle sensing capabilities may enable aircraft to operate with VFR separation minima in IMC [6]. Such a development would decouple the weather influence factor from the separation standards mechanism and provide consistent sector capacity regardless of visual or instrument conditions.

Finally, a third set of potential approaches focus on the use of new CNS technologies that reduce separation requirements by relying upon precisely defined 4D flight trajectories. In one such approach, flights may be assigned to routes that have small containment boundaries (well below the IFR separation requirements) "when special electronic, area navigation or other aids enable the aircraft to closely adhere to their current flight paths." [15]. The PBN Required Navigation Performance (RNP) effort is the primary example of this approach. RNP relies upon satellite-based navigation, ground-based and satellite-based augmentation systems, and onboard performance monitoring and alerting to provide the high degree of operational integrity required [16]. The most advanced RNP procedures currently allow separation from obstacles as little as 0.2 NM in IMC [17]. Future implementations of Trajectory Based Operations (TBO) [18] or "free flight" operations [19], [20] may enable aircraft to operate on dynamically defined 4D flight trajectories with similarly reduced containment boundaries.

3. *Controller and Pilot Workload Mechanism*

Air traffic controller workload is commonly perceived as the capacity limiting mechanism for en route sectors. Furthermore, current helicopter operators in São Paulo and Boston have encountered controller workload limitations in low altitude airspace. For example, Fig. 5 displays the São Paulo "helicontrol" airspace. This airspace volume supports as many as 800 helicopter operations per day interspersed with commercial aircraft operations to or from Congonhas airport. Clustered flight track data for arrivals and departures from Congonhas have been indicated in red and green, respectively, in Fig. 5. To manage this complex mixed traffic scenario, Brazilian ATC established special entry and exit points to the airspace for helicopters, special routes and procedures that must be followed, and most importantly, a limitation on the number of simultaneous helicopter operations in the airspace to <u>six</u> helicopters for controller workload and safety purposes [21]. This workload-derived limitation has constrained initial UAM efforts by Airbus Helicopters' Voom program. Similar limitations are anticipated in other cities. Interestingly, on April 26, 2018 the Brazilian Aeronautical Command released a new

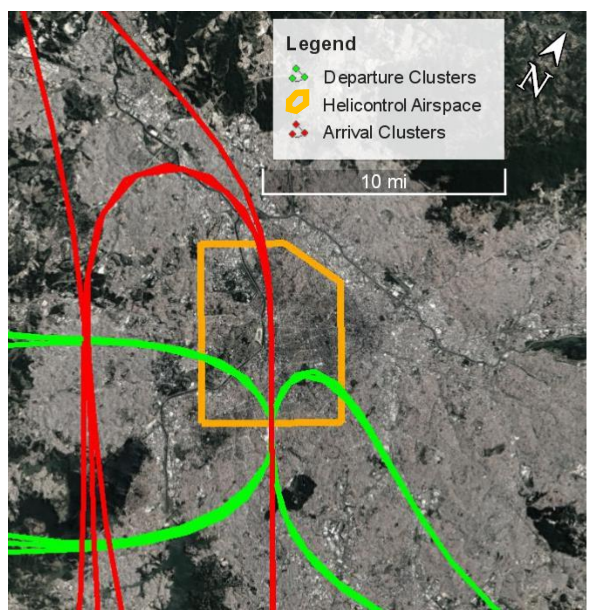

Fig. 5 São Paulo "helicontrol" airspace interaction with Congonhas airport operations. *Map © 2018 Google. Map Data: DigitalGlobe, CNES/Airbus*

circular that removed the simultaneous operating limit and appears to enable controllers to manage more than six helicopters, workload permitting [22].

In addition to air traffic controller workload limitations, pilot workload may also influence achievable levels of airspace capacity. When applying visual separation, pilots must collect and process information on the location, speed, and trajectory of nearby aircraft or obstacles. They collect this information through visual scanning and auxiliary sources such as radio announcements, navigational charts, and proximity sensors. The complexity of this task increases non-linearly with the number of nearby aircraft in an airspace and the speed at which the aircraft is travelling. Pilots widely acknowledge the challenge of flight in current high-density VFR operating environments such as on arrival to the Oshkosh airshow or transiting through the Hudson River SFRA. If UAM operators increase the flight density above cities to or beyond the levels currently experienced in these special VFR operating areas, they may encounter flight safety challenges and be constrained by pilot workload limitations.

Numerous proposals have been advanced to reduce controller and pilot workload. These range from advanced decision support tools to fully automated trajectory assignment and conflict resolution algorithms. Current high-density aircraft operations at the Oshkosh airshow and the British Grand Prix have relieved the controller workload mechanism in part by dramatically increasing the number of controllers supporting the airspace; in the case of Oshkosh as many as 64 controllers are utilized.

B. Constraint Severity Representation

Low-density UAM operations were not anticipated to cause severe ATC capacity limitations as the ATC system regularly supports a small number of charter helicopter and general aviation operations today. However, high densities of UAM flights beyond those experienced today were anticipated to limit UAM system scalability. The usefulness of this notional relation can be improved by correlating the concept of "constraint severity" with a metric of UAM system performance.

This research proposes that the salient impact that insufficient ATC scalability (i.e. insufficient sector capacity) will have is to increase the average delay a UAM operation may be subjected to. Delay is defined as the additional time required for an aircraft to complete its mission in the presence of congestion or ATC control actions compared to the average uninhibited mission completion time. Delay may be accrued by a flight through multiple means including ATC assigned ground or airborne holding, diversion around weather or TFRs, or sequencing delays into an airport.

Fig. 6 presents the relationship for average delay experienced by users accessing a capacity constrained resource, such as an airspace sector. Two thresholds of interest are also indicated in Fig. 6. The theoretical capacity (also referred to as "throughput" capacity in some literature [23]) represents the maximum capacity of a sector without restriction on the amount of delay accrued by flights. Practical capacity represents the achievable sector capacity if aircraft are only allowed a maximum average delay. These two metrics reveal the competing objectives of controllers to achieve optimal utilization of an airspace or airport asset while minimizing delay costs to the operators.

The shape of the delay curve for a specific airspace is set through the mechanisms introduced in Fig. 3. Given this relation, the average delay experienced by flights in a sector is an appropriate metric for the ATC scalability constraint severity because it represents the limitation that will be applied to UAM operators seeking to further increase the number of flights in that sector.

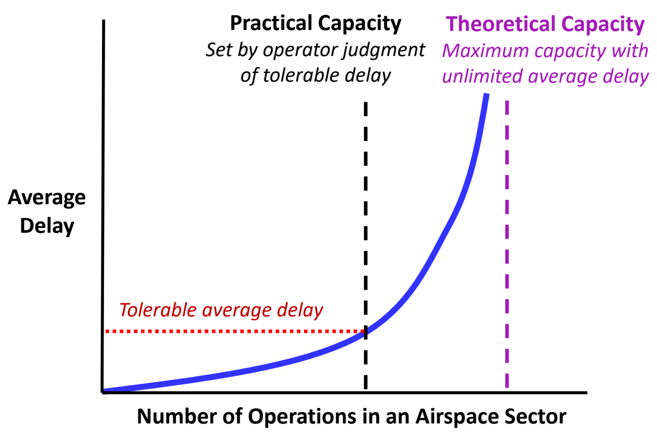

Fig. 6 Average flight delay in an airspace sector as a function of demand [23].

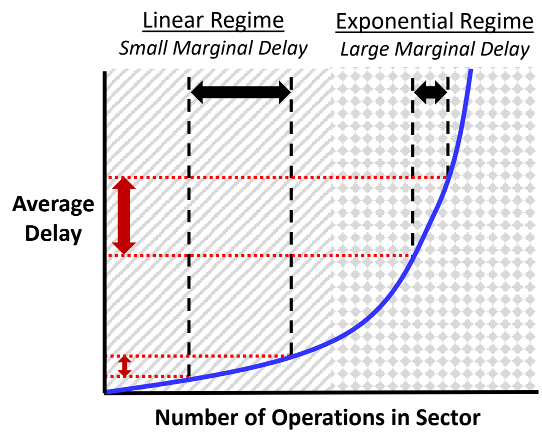

Fig. 7 Regimes of marginal increase in average flight delay.

The marginal increase in average flight delay in response to the addition of an operation in the sector may be segmented into two regimes as shown in Fig. 7. For airspace sectors that have a much larger capacity than the demanded number of operations, the addition of a single additional flight will have little impact upon the average delay experienced. However, for airspace sectors that receive demanded loads near their theoretical capacity, the average delay increase for an additional flight may be exponential. In this case the addition of one flight to the sector could significantly increase average delay for all flights.

Relieving the ATC scalability constraint in a sector may therefore be visualized as shifting the delay curve to the right. The location and shape of the curve is influenced by the three mechanisms presented in Fig. 3. As displayed in Fig. 8, increasing sector capacity (shifting the curve to the right) effectively enables more aircraft operations to occur in the sector while accruing the same tolerable delay; this is equivalent to saying that the practical capacity of the sector was increased. Fig. 8 also indicates how various operational and technological factors may shift the delay curve.

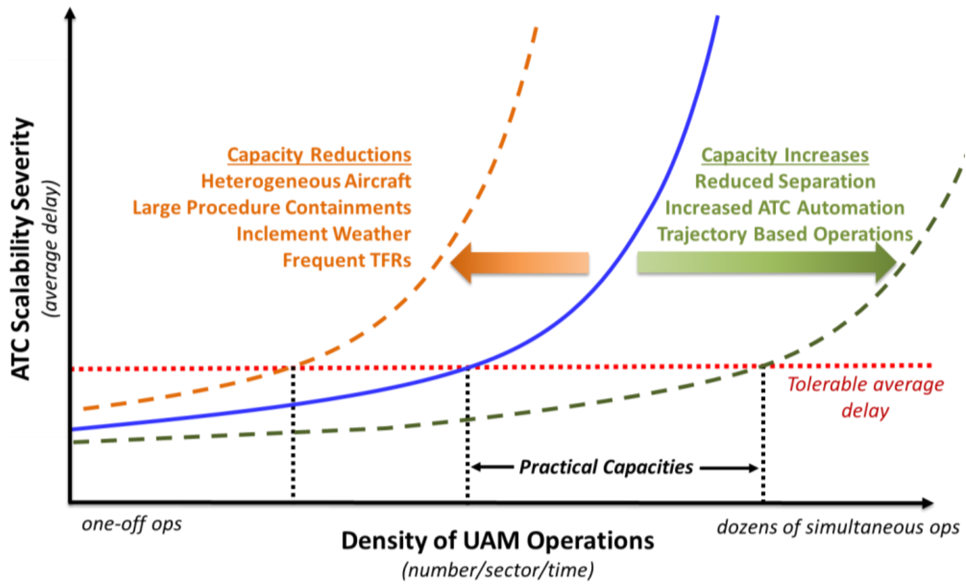

Fig. 8 Dependence of ATC scalability constraint on network density with example capacity influence factors.

IV. Ground Infrastructure Availability

Airport availability is perhaps the leading operational constraint for commercial airline operations today. Many large cities have operational demand that significantly exceeds the capacity of their airport(s) [24], [25]. In order to avoid chronic and excessive delays, some airports have implemented slot restrictions or demand management efforts to avoid becoming saturated. Furthermore, when inclement weather reduces the capacity of airports, ATC is forced to implement traffic management initiatives such as ground stops or airborne holding. These actions further hinder the air transportation system. Finally, as cities have expanded some communities have opposed the noise and air quality impacts of aircraft and forced the relocation of airport infrastructure further out on the periphery of the city [26]. This has resulted in airports and commercial airline services which are less accessible to a majority of people.

It has been proposed that emerging UAM operations may similarly be constrained by the lack of capacity or accessibility for their Takeoff and Landing Areas (TOLAs), be they airports, heliports, vertiports, "skyports", or some other form of ground infrastructure [1], [3]. Evaluation of current aviation infrastructure in Los Angeles, Dallas, and Boston found that while each of these cities had over 200 existing heliports and airports, these facilities were by and large poorly suited for UAM operations because of their low throughput capacity and sub-optimal locations (low accessibility to areas of demand).

A mismatch between UAM demand and the availability of appropriate ground infrastructure to support these operations may lead to a variety of operational challenges including:

- Increased first and last mile ground transportation requirements adding time, expense, and complexity to trips
- Increased surface and airborne congestion in proximity to TOLAs
- Difficulty staging aircraft to meet demand, especially during peak operating periods
- Low resilience and recoverability to system perturbations

A. Mechanism and Factor Influence Mapping

The ground infrastructure availability constraint emerges through two high-level influence pathways, namely the lack of TOLA throughput capacity and the inability to locate a TOLA in a desired area (i.e. its accessibility). Airport design and throughput capacity estimation is a well-researched field, albeit with few studies focused specifically on VTOL aircraft and heliports. Through the review of airport system texts [26], [27], FAA advisory circulars for airport and heliport design [28]–[30], and associated capacity literature [31], [32], numerous factors that may influence TOLA availability were identified.

A mapping was developed to group related factors together that influence TOLA availability through a common mechanism. Fig. 9 displays how each of the identified influence factors (in orange) act through three mechanisms (in blue) to set the practical capacity of a TOLA or influence where it may be located; these are the two components of the TOLA availability constraint (in black).

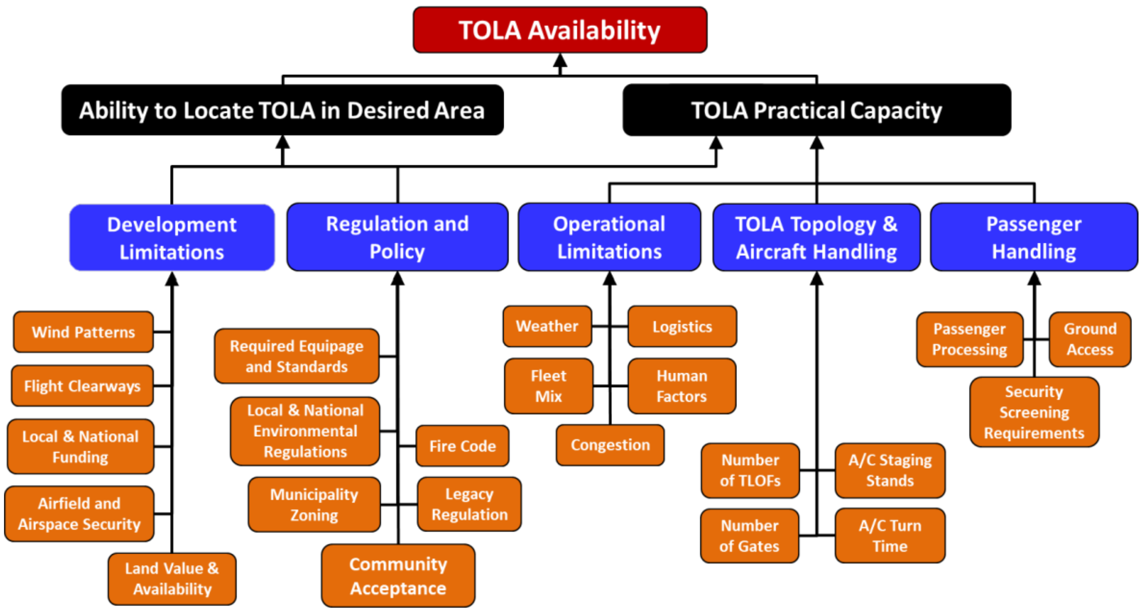

Fig. 9 TOLA availability influence diagram.

All five of the mechanisms were determined to influence the capacity of TOLA, however only the "development limitations" and "regulation and policy" mechanisms were found to affect where (geographically) a TOLA could or could not be built. The follow sub-sections discuss each mechanism in greater detail and describe how their various dependent factors may influence the overall availability of TOLA infrastructure for UAM operations.

1. Development Limitations Mechanism

"Development Limitations" refer to a set of influence factors that are either physically or programmatically present during the planning, design, and construction of a TOLA. These factors influence the feasibility of creating a TOLA in a particular location and may also place limitations upon the TOLA's capacity. For example, prevailing wind patterns or the interaction of winds with rooftops and nearby buildings influence where a TOLA may be located, how it must be constructed, and what flight procedures it may use. Similarly, the footprint of potential locations may constrain the maximum possible size of the TOLA. The use of public land or funding may affect who can use the facility and for what operations they may use it.

2. Regulation and Policy Mechanism

Aviation surface infrastructure is potentially subject to regulation and policy requirements from numerous stakeholders. Local municipalities have authority over the siting, design, and surface operations of TOLAs within their jurisdiction. State or federal environmental regulations may also apply to TOLA development and operation. Local fire codes can influence the design of TOLA facilities and require specific equipment (such as fire suppression systems and safety nets). Local municipal codes may specify the design standard the TOLA must be built to (such as FAA advisory circular 150/5390-2C for heliports), or require insurance policies with their own set of design and operational restrictions. Finally, local jurisdiction policy is relatively fluid and subject to change. Poor community acceptance of operations from a TOLA may rapidly stimulate restrictions for its use. Removing burdensome legacy restrictions, however, may be a slower process.

A scan of numerous municipalities throughout the United States revealed significant variability in the regulatory burden placed upon TOLA developers. For example, in Grand Forks, North Dakota, local ordinance only allows helicopters to operate from certified and charted airports or heliports. In Monterey County, California, helicopters are allowed to land on unimproved private property as long as they are not within 1000ft of a K-12 school; no design standards for TOLAs are prescribed. Similar to the "development limitations" mechanism, the factors within this mechanism display great variability and sensitivity to the local ecosystem surrounding the development and use of a TOLA.

3. TOLA Topology & Aircraft Handling Mechanism

These four influence factors most directly set the aircraft throughput capacity of a TOLA. TOLA topology is set by the number of Touchdown and Liftoff (TLOF) surfaces at which UAM aircraft may alight or depart from, the number of gates at which the aircraft may interact with passengers and services, and the number of staging stands for extra aircraft. These constitute the three key components of a TOLA's built infrastructure and influence aircraft throughput. The fourth factor, the average turn-time for a UAM aircraft, determines how long a single operation will use each of these three components of the TOLA infrastructure.

Fig. 10 displays a notional ConOps for a generic TOLA. The role that each of the four influence factors play in TOLA operations is evident. Aircraft arrive to one or more TLOFs through the use of one or more approach procedures. If the TOLA is equipped with gates then the aircraft may taxi off the TLOF to an available gate; if no gates exist or are available then it may be possible to turn the aircraft on the TLOF. A minimum turn-time is required to complete a variety of activities. These activities could include unloading passengers and baggage, fueling (or recharging) the aircraft, cleaning the cabin and replenishing consumables, or loading new passengers and luggage. Once the turn has been completed the aircraft may taxi to the same TLOF it arrived at or a different TLOF and depart. If staging stands are available (in addition to the gates), then aircraft may be prepositioned there and deployed to increase achievable TOLA departure capacity, or aircraft may be extracted from service to the staging areas to increase achievable TOLA arrival capacity. It should be noted that there are numerous other potential ConOps for a TOLA besides the one presented in Fig. 10 such as the use of conveyer belts that replace gates.

As suggested above, the throughput capacity of a TOLA is dependent upon the ratio of arrivals to departures. Airport capacity is often described by a "capacity envelope" which is a convex function that displays the frontier of maximum feasible arrival and departure rate for all ratios. The airport can theoretically operate at any arrival and departure rate on or within the convex frontier.

Capacity envelopes were developed analytically for UAM TOLAs in this research to display the influence of the four aircraft handling factors. Fig. 11 displays capacity envelopes developed for three TOLAs with a single TLOF and varying numbers of gates and pre-staged aircraft. All cases assumed deterministic operating times, that only one aircraft could simultaneously be on approach or departure or any element of the TOLA, that staged aircraft were prepared to depart immediately, and that an aircraft could only be turned on the TLOF if the TOLA had no gates. Furthermore, 15 second approach and departure operations were assumed, a 30 second minimum turn-time, and zero seconds required for taxing (i.e. taxing time was considered to be included in approach and departure time). These approach, departure, and minimum turn-times are not proposed to represent feasible UAM and TOLA operational capabilities, but rather were selected to display interesting characteristics of the TOLA capacity envelopes for this notional analysis.

A variety of insights may be gained from Fig. 11. First, the capacity envelopes for the three TOLA scenarios presented in Fig. 11 have lower and upper surfaces with positive slope and a non-unique relation of arrivals to departures. A defining characteristic of traditional airport capacity envelopes is they appear as a convex hull with no regions of positive slope, or more specifically the number of departures is always a monotonically decreasing function of arrivals. However, this attribute of airport

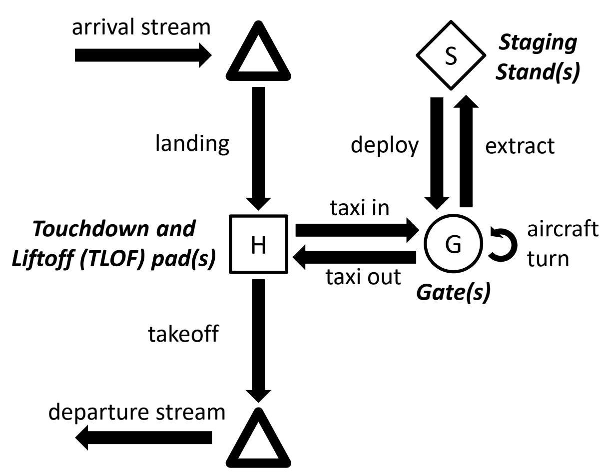

Fig. 10 Notional TOLA ConOps displaying role of the TLOF, gate, staging area, and turn time.

capacity envelopes relied upon the assumption that the airport had sufficient gate and staging capacity to accommodate any number of arrivals or departures the runways could support during the metric time interval. This assumption is not valid for small or moderately sized UAM TOLAs that do not have many gates or staging areas.

The number of gates and staging areas in the three scenarios presented is significantly less than the achievable 5 minute throughput capacity of the single TLOF under the assumptions made. As a result, there are large regions of arrival and departure rates where aircraft could theoretically land or depart from the TLOF but would have no available gate or staging area to move off the TLOF to or onto the TLOF from. For example, in TOLA scenario 2 there were only 2 gates at which to place aircraft. This means that no more than 2 aircraft could ever arrive at the TOLA before at least one departure occurred. This trend indicates the importance of gate and staging area capacity if an unbalanced number of arrivals or departures are to be conducted, such as during morning or evening commuting hours. Note that as staging/gate capacity is increased, such as in scenario 3, the capacity envelope "fills out". With enough staging/gate capacity the capacity envelope will return to a shape such that departure capacity is monotonically decreasing.

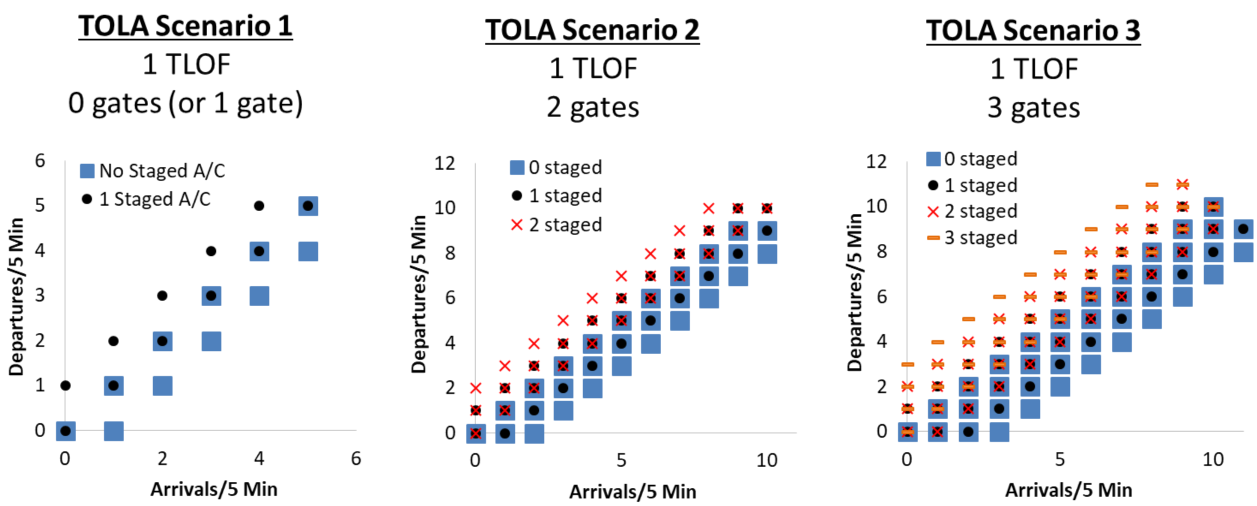

Fig. 11 Example capacity envelopes for three variations of TOLA topology.

A second insight from Fig. 11 is the variance in marginal TOLA throughput to the addition of gates. As can be seen from scenario 1 to scenario 2, the addition of one gate (from one to two) resulted in a significant increase of maximum throughput from five arrivals and departures in five minutes to 10 arrivals and departures in five minutes. However, the addition of a third gate only increased the maximum throughput to 11 arrivals and 10 departures.

The much larger marginal throughput gain from scenario 1 to 2 than 2 to 3, both representing the addition of one gate to the TOLA, arose due to a shift in which aircraft handling influence factor constrained TOLA throughput capacity. In scenario 1 the turn-time of an aircraft at the single gate was the dominant factor limiting throughput. In this scenario the TLOF had capacity to support more takeoffs and landings but was underutilized. However, in scenario 2 the number of gates was increased such that the rate at which aircraft could be processed was roughly equal to the TLOF processing rate, and both pieces of infrastructure had nearly 100% utilization. In scenario three the number of gates was increased so that aircraft could be processed more rapidly at the gates than the TLOF could handle them. Therefore the TLOF was fully utilized and became the dominant factor limiting further throughput gains no matter how many additional gates were added (though more gates would still "fill out" the capacity envelope due to aircraft staging effects).

Future work will develop capacity envelopes for TOLAs with more complex infrastructure (more TLOFs, gates, and staging capacity). Furthermore, the sensitivity of marginal throughput gain to changes in each of the four TOLA topology and aircraft handling influence factors shall be determined for each TOLA architecture.

4. Passenger Handling Mechanism

In addition to aircraft handling, passenger handling is another key mechanism that influences the throughput capacity of current airports. Since September 11, 2001, increased security screening requirements have created a new bottleneck (capacity constraining point) in many airports and limited the ability of passengers to reach aircraft, even if aircraft were prepared to leave. Similarly, increasing demand and the number of flights has overburdened the public transit and vehicular access capabilities of some airports limiting the number of passengers that can physically get to or from the airport. These two passenger handling influence factors have resulted in new infrastructure investments by some airports and municipalities to restore aircraft throughput as the limiting mechanism and most efficiently use the airport and aircraft.

TOLA facilities, especially those that will retrofit existing rooftops or fit within size constrained inner-city lots, may be especially sensitive to the passenger handling mechanism. Additional ground access infrastructure, such as dedicated roadways, parking lots, pickup/dropoff aprons, and elevators may be especially challenging to develop alongside legacy infrastructure in densely built city environments. Furthermore, TOLAs built in space constrained areas may sacrifice terminal space (passenger handling capacity) for increased airfield space (aircraft handling capacity) and create issues for effective passenger processing and security scanning.

5. Operational Limitations Mechanism

While the aircraft and passenger handling mechanisms jointly define the maximum throughput capacity of a given TOLA in ideal operating conditions, the "operational limitations" mechanism describes influence factors that may degrade the performance of the TOLA from day to day in actual operation. For example, the weather conditions, fleet mix of aircraft, and the amount of air traffic congestion may reduce aircraft throughput on the airfield or TOLA procedures as discussed in Section III. Furthermore, atypical traffic or public transportation congestion (such as during rush hour) may significantly reduce passenger throughput at the TOLA. Finally, workload limitations of the TOLA controller or ground staff, as well as operating logistics in terms of the number of pre-staged aircraft, may further influence the achieved practical throughput capacity of a TOLA.

B. Constraint Severity Representation

Similar to the ATC scalability constraint, this research proposes the salient impact that insufficient ground infrastructure availability will have is to increase the average delay a UAM customer would experience on a trip. Delay is defined here as the additional time required for a customer to complete their door-to-door mission due to throughput capacity limitations at the TOLA or excess first mile/last mile travel time required if a TOLA was not located at the origin and destination. Delay may be accrued by a customer through multiple means including congestion travelling to or from the TOLA, congestion in the terminal, or congestion during aircraft services, taxiing, departure, or arrival.

UAM system operations in a region represent a classic Traffic Flow Management (TFM) problem where the goal is to minimize door-to-door travel time for each passenger. An intuitive way to think about optimizing such a network is by framing each passenger as seeking a "path of least delay", which is similar to an electric circuit's "path of least resistance". In this formalism, delay as defined above is an effective metric through which the influence of TOLA geographic location and practical capacity can be understood.

Fig. 12 displays how the infrastructure availability constraint may be represented by accrued delay in a notional UAM service scenario. In Fig. 12, a customer enters the UAM system at an arbitrary geographic location. Because there is no TOLA onsite, the four nearest TOLAs in the area are identified as potential points of departure. Travel times are estimated from the customer to each TOLA, and the processing time and time to departure at each TOLA is also estimated. These two times jointly represent the total delay that the customer would experience if selecting (or assigned) each TOLA compared to a notional facility with zero delay located at the customer's origin.

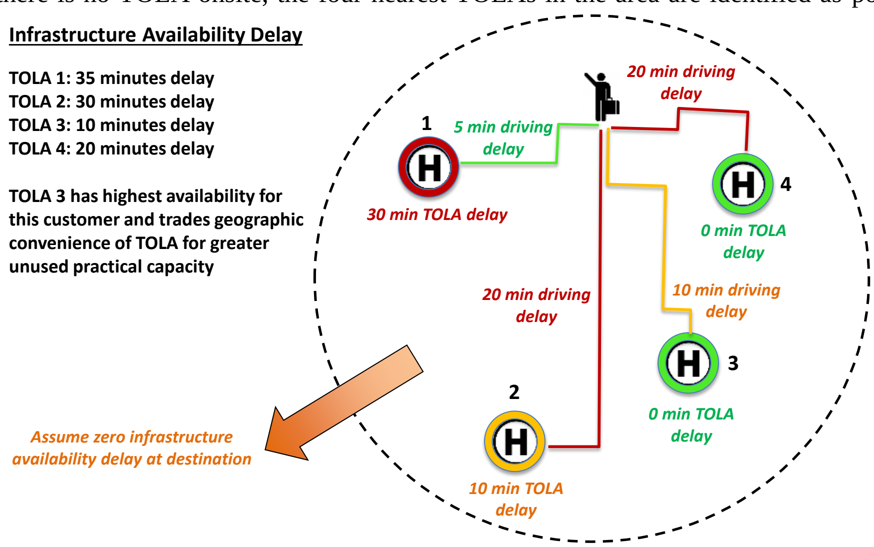

Fig. 12 Example framing of infrastructure availability as delay in a notional UAM system.

For the sake of simplicity, the situation presented in Fig. 12 ignores the other half of the TOLA availability constraint dealing with arrival at the destination TOLA and last mile transportation. It should also be noted that the use of delay as a metric for ground infrastructure availability does not imply that an "optimized" solution would yield zero delay for every customer as that would require a TOLA to be located at the origin of every potential customer. Instead, it is likely the TOLA availably objective of a UAM system would be to achieve an acceptable average TOLA availability (average delay) for a set of geographic areas or key customer origins in the network.

Fig. 13 displays the resultant constraint severity relation for ground infrastructure availability as a function of UAM system density (i.e. the number of operations demanded at a TOLA). The function has the same shape and properties as the delay function presented in Fig. 6 and Fig. 7. The location and shape of the curve for any specific TOLA is influenced by the five mechanisms presented in Fig. 9. As displayed in Fig. 13, increasing TOLA practical capacity results in a shift of the curve to the right as more operations may be serviced before the threshold acceptable average delay is reached. Furthermore, an increase in the accessibility of the TOLA to the origin (destination) of the customer trip reduces the required first mile (last mile) travel times. This impact may be visualized as shifting the delay curve vertically downwards as the accessibility of the TOLA increases. Fig. 13 also indicates how various influence factors may shift the delay curve through accessibility or practical capacity enhancements and reductions.

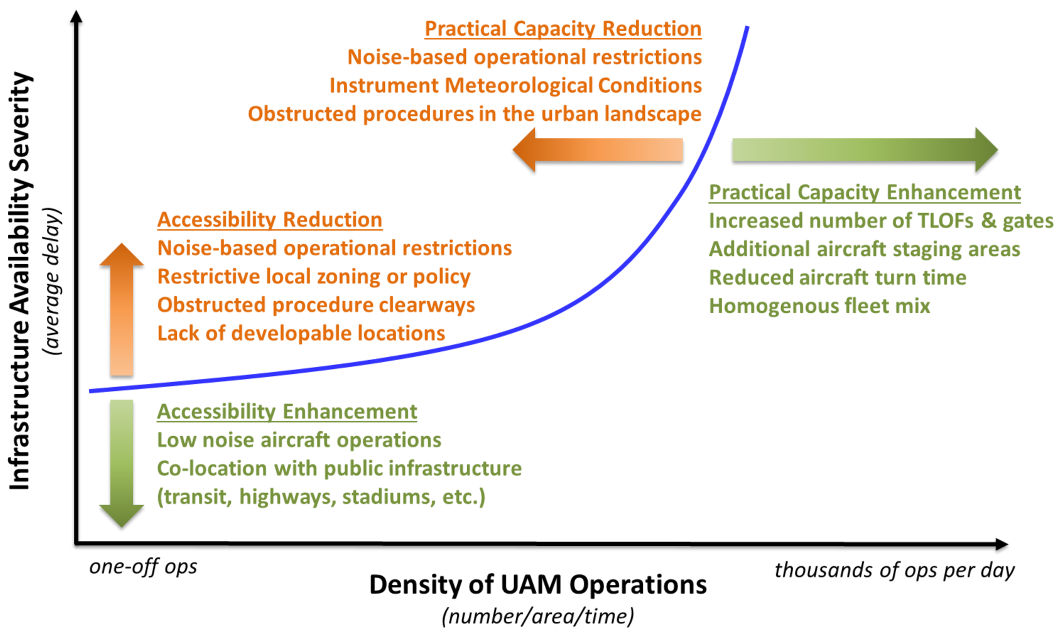

Fig. 13 Dependence of infrastructure availability constraint on network density with example capacity influence factors.

V. Noise and Community Acceptance

Aircraft and helicopter noise has become 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 have recently driven significant political and legal community action and are the primary drivers of the community acceptance constraint [33], [34].

Poor community acceptance 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. [35] 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, as displayed in Fig. 3 and Fig. 9, community acceptance is an influence factor for both the ATC scalability and ground infrastructure availability constraints. This means that poor community acceptance may also trigger either the ATC or infrastructure constraints. Table II 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.

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 [36], and prompted the New York City Council to reduce the number of helicopter tours by half in 2017 by prohibiting 30,000 annual flights [37].

Table II. 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

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 [3], [38]–[40]. 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 [41].

Rather than relying solely upon vehicle technologies to reduce noise emission and resultant community annoyance, Ref. [42] 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

However, despite significant progress in many aspects of this balanced approach (including the reduction of jet aircraft source noise by half since their introduction, the implementation of noise abatement procedures at many airports, the insulation of residences near airports, and the adoption of fly neighborly best practices by many helicopter pilots) aircraft and helicopter noise continues to be the leading challenge for community acceptance of aviation activities and remains a key potential constraint for limiting the scalability of UAM systems.

A. Mechanism and Factor Influence Mapping

Previous literature was reviewed in order to identify the key mechanisms through which aircraft flight affects community annoyance. The term "annoyance" is used in the sense of describing "all negative feelings such as disturbance, dissatisfaction, displeasure, irritation, and nuisance" towards an aircraft operation [43]. In the literature, the most frequently discussed negative impacts of aircraft noise are:

- <u>Speech Interference</u>: aircraft noise may degrade ability to carry out normal speech [34], [44]
- <u>Sleep Disruption</u>: nighttime indoor noise levels have been found to influence awakenings and quality of sleep [34], [45]–[48]
- <u>Fear/Startle</u>: low level flyover, loud flights, or a rapid onset of aircraft noise may lead to sudden fear (startle) or enduring fear of operations [34], [49]–[53]
- <u>Health Impacts</u>: long-term noise exposure has been found to increase the risk of hypertension, cardiovascular disease, and stroke as well as reduce cognitive performance [54]–[57]
- <u>Economic impacts</u>: 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 III presents the results of a literature scan to identify non-acoustic factors (referred to recently as "virtual noise" [58]) that may influence an individual's annoyance to aircraft noise. The first column lists out 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 (or not engage) in public action criticizing or supporting 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.

Table III. 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	[46], [47], [50]
	Time of Day	high	No	[43], [46], [48], [49], [59], [60]
	Day of Week	moderate	No	[59]
	Weather	moderate	No	[43], [59]
	Ambient Noise	moderate	Yes	[46], [60]–[62]
	Public and Political Profile	high	Yes	[59], [61]
Listener or Community Factors Mechanism	*Attitudes*			
	Fear related to noise source	high	Yes	[50], [51], [63], [64]
	Belief that noise situation will worsen	moderate	Yes	[64]
	Belief noise source is important to community	moderate	No	[50], [63], [64]
	Familiarity/adaptation	high	Yes	[44], [47], [61], [64]
	Personality Traits			
	Noise sensitivity	high	No	[50], [51], [63], [64]
	Anxiety/neuroticism/emotionality	moderate	No	[65]
	Control and coping capacity	moderate	Yes	[64]
	Trust in authorities and perceived fairness	high	Yes	[50], [64]
	Demographics			
	Age	low	Yes	[43], [51]
	Gender	negligible	No	[50], [51], [61], [63]
	Socio-economic status	negligible	Yes	[50], [51], [63]
	Income	negligible	Yes	[50], [51], [63]
	Education level	negligible	Yes	[50], [51], [63]
	Homeownership	negligible	Yes	[50], [51], [63]
	Marital status	negligible	No	[50], [51], [63]
	Type of dwelling	negligible	No	[50], [51], [63]
	Dependency on noise source	negligible	Yes	[50], [51], [63]
	Use of the noise source	negligible	Yes	[50], [51], [63]
	Length of residence	negligible	Yes	[50], [51], [63]
Secondary Effects Mechanism	Correlation of noise to air quality	moderate	No	[50]
	Correlation of noise to dust	moderate	No	[50]
	Correlation of noise to fumes	moderate	No	[50]
	Vibrations due to low frequency noise	moderate	Yes	[66]

The purpose of this 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 [58], [65].

Reviewing Table III 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 describing "situational factors", "listener factor", and "secondary effects", respectively. Furthermore, the author proposes another relevant 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.

Fig. 14 displays how each of the four non-acoustic mechanisms and the single acoustic mechanism translate aircraft noise emissions and non-acoustic operational impacts into noise annoyance and 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.

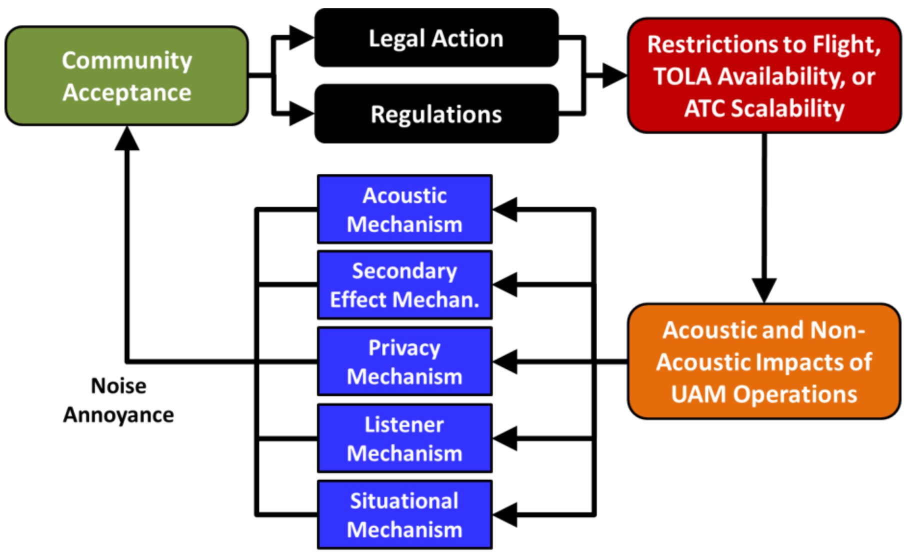

Fig. 14 Noise and community acceptance influence diagram.

Unlike the influence diagrams for ATC scalability or ground infrastructure availability, the community acceptance influence diagram was formulated as a feedback loop. This structure captured the dynamic nature of the community acceptance constraint where the "acceptable" level of noise to a community and the resultant constraint severity (level of limitation) for operators is determined when equilibrium is reached in the feedback loop. In other words, unlike the influence diagrams presented in Fig. 3 and Fig. 9 where the influence factors linearly lead to the operational constraints for ATC and ground infrastructure, there is a more complex relationship for community acceptance.

A second important consequence of the unique structure of this constraint is that in order for aircraft noise to result in operational restrictions, not only must the annoyance mechanisms (represented in blue in Fig. 14) 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. 15 decomposes the "acoustic and non-acoustic impacts of UAM operations" block from Fig. 14 into much greater detail revealing 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 III. The privacy mechanism influence factors are proposed by the author. The acoustic mechanism influence factors were drawn from Refs. [65], [63], and [67]. Fig. 15 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.

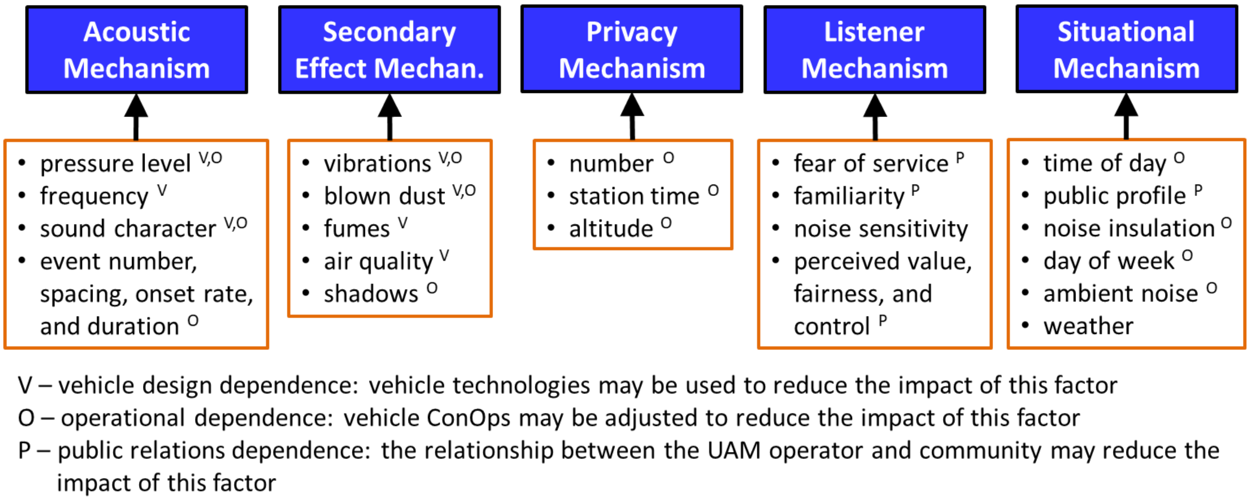

Fig. 15 UAM influence factors on noise annoyance with indicated dependencies upon vehicle technologies, operations, or public relations.

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 III for a detailed discussion of each influence factor presented in Fig. 15.

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 [67]
- the character of the sound is impulsive (such as helicopter blade slap) [63], sharp (few low-frequency tones), rough, or exhibits strong tonality such as purse tones or a buzzsaw effect [65]
- 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 [3], [68], [69].

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 [66]. Electric aircraft technologies are anticipated to all but 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 such as in *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 [70]. The authors therefore propose 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 [50], [65].

5. *Situational Mechanism*

The situational mechanism describes numerous 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.

B. Constraint Severity Representation

As briefly introduced above, developing a numerical representation of annoyance and community acceptance of aircraft noise is a significant and ongoing research challenge. A majority of metrics used today, such as DNL, EPNL, and SEL, are nearly entirely based upon the acoustic mechanism with some adjustments for non-acoustic factors (such as a penalty for nighttime operations). Despite these adjustments, traditional metrics have been criticized because community annoyance has been pervasive even when aircraft noise exposure remains below the supposed threshold of "acceptability" according to the metrics. Furthermore, communities with different attributes and located in different geographic areas have been shown to vary significantly in their annoyance to equivalent noise exposure [66].

An additional challenge for this research was that rather than purely correlating noise exposure to annoyance, the purpose of this study was to correlate operational limitations imposed on UAM systems (the *impact* of the community acceptance constraint) with noise exposure from these operations. This required the consideration of the two public action pathways indicated in black in Fig. 14 in addition to the mechanisms indicated in blue in the figure. The importance of considering this secondary public action step was essential for anticipating actual constraint severity for UAM operations. For example, while traditional "dose-response" functions may indicate that a given noise exposure level will only "highly" annoy 1% of people in a community, if that 1% is politically active or more inclined to engage in public action then they may create greater operational constraints than another community that has 75% of people highly annoyed but does not have the capacity to affect change.

Considering these challenges, this research did not attempt to develop an analytical relation of aircraft noise exposure to community acceptance constraint severity, but rather leveraged existing metrics as a baseline from which to evaluate the general magnitude and direction of the impacts various operational, technical, or public relations mitigation approaches by UAM operators may have.

1. *Translating the number of UAM operations to a percentage of the community that is "highly annoyed"*

A two-staged approach was taken in this research to evaluate community acceptance impacts upon UAM operations. First, a traditional "dose-response" function was used to translate the noise exposure generated by some number of UAM operations into a percentage of the community that was likely to be highly annoyed. Fig. 16 displays an example dose-response function where the x-axis has been adjusted for the representative purposes in this analysis.

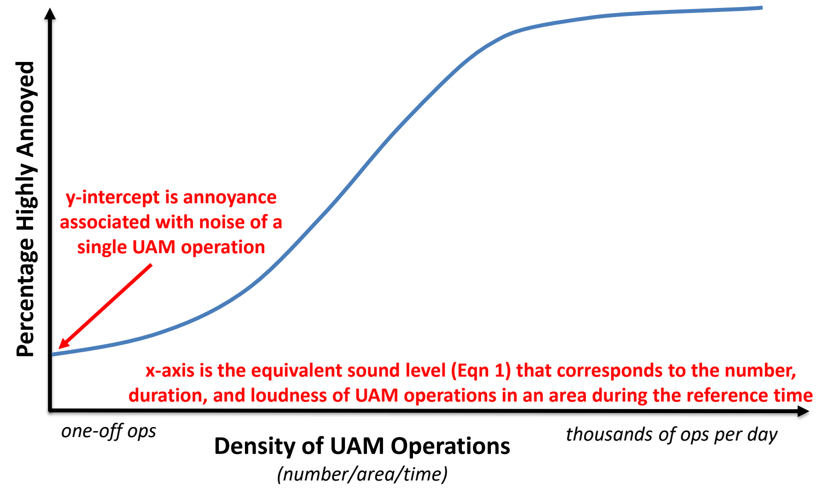

Fig. 16 Notional dose-response function relating density of UAM operations to annoyance

The x-axis is the number of UAM operations that occur within the community of interest within a specific time period. The number and characteristics of each operation may be converted into a typical equivalent noise exposure level through Eqn. 1 where "t" is the duration and "L" is the loudness of each event during reference time "T". The percentage of individuals highly annoyed may then be found through an appropriate dose-response function. The conversion from number of operations to noise exposure explicitly takes into account three of the acoustic influence factors including loudness of each flight, the duration of the exposure from each flight, and the number of flights that occur in the time period.

$$L_{eq} = 10Log_{10}\left(\frac{t_1 * 10^{\frac{L_1}{10}} + t_2 * 10^{\frac{L_2}{10}} + \cdots + t_n * 10^{\frac{L_n}{10}}}{T}\right) \qquad \textbf{Eqn. 1}$$

In order to represent the impact of the remaining acoustic factors and non-acoustic mechanisms on constraint severity, the concept of a Community Tolerance Level (CTL) proposed by Ref. [66] was expanded upon in this research. Fig. 17 displays the concept of the CTL which is a metric that describes community variability in the dose-response relationship. As may be seen, the variability largely manifests as a horizontal shift of the standard dose-response curve. This is a useful observation as it means the shape of the standard dose-response function remains relatively representative of annoyance despite the influence of the remaining acoustic factors and non-acoustic mechanisms. Also in Fig. 17, the authors have identified those acoustic factors and non-acoustic mechanisms that they anticipate will impact the CTL variability for specific communities.

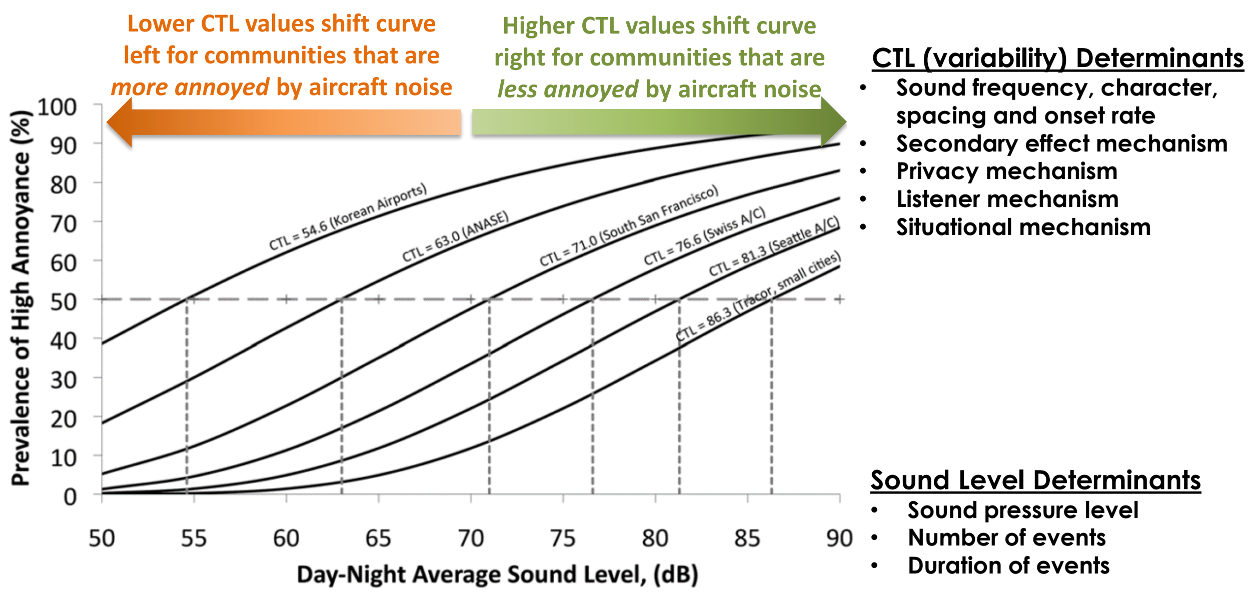

Fig. 17 Community Tolerance Level (CTL) as introduced by Ref. [66] with proposed acoustic and non-acoustic determinants of CTL variability and sound exposure levels.

Although no effort was made in this research to analytically or empirically determine the exact influence of the non-acoustic influence factors on CTL, the magnitude and direction of likely impacts of specific mechanisms and influence factors upon CTL were hypothesized. Fig. 18 displays a few of the most significant (having a greater magnitude of impact) influence factors and the direction anticipated for the shift they cause in the dose-response curve. The magnitude of the anticipated change directly relates to the "significance" of the influence factor identified in the annoyance literature as presented in Table III.

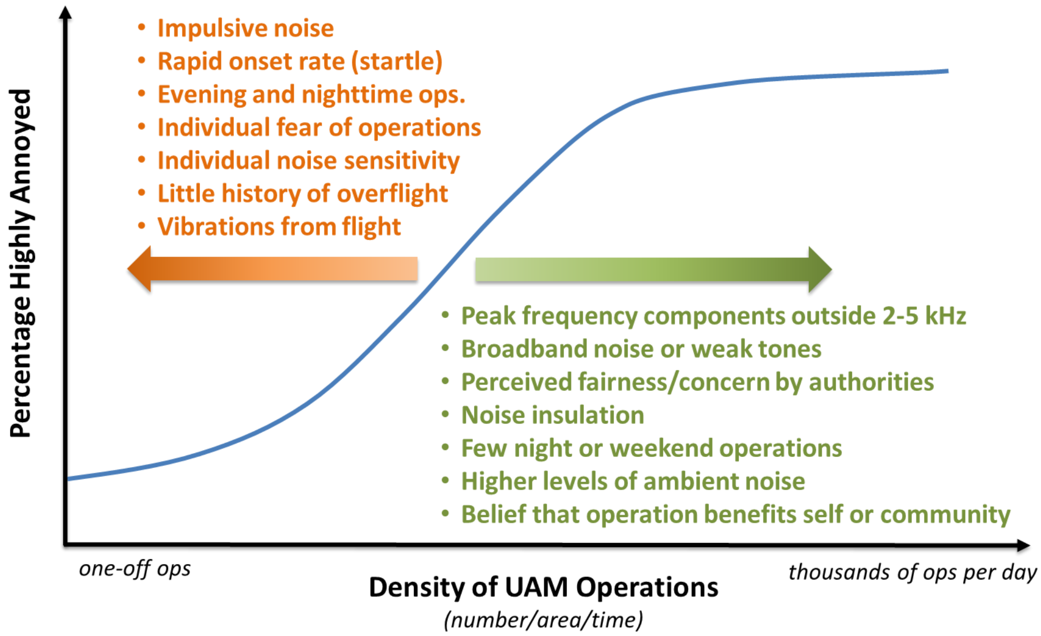

Fig. 18 Effect of the most significant community acceptance influence factors on the general dose-response function.

2. Mapping the percentage of highly annoyed individuals to the probability a UAM operational limitation emerges

The second stage of the approach to evaluate community acceptance impacts upon UAM operations was to relate the percentage of highly annoyed community members to the probability that an operational constraint would manifest. The conversion of community annoyance to operational limitations requires public action in the form of legal or regulatory action by the communities, as shown in Fig. 14. The public action potential of communities was shown in Table III to depend upon many of the identified influence factors such as trust in the authorities and fear of the service. Furthermore, eight of the 11 demographic factors (not considered to constitute an annoyance mechanism) were suggested in the literature to influence the probability that an individual would be able to affect change through public action.

Fig. 19 displays how these public action considerations complete the mapping of UAM operations to the community acceptance constraint severity. First, the y-axis no longer represents the percentage of the community that is expected to be highly annoyed as it did in the dose-response function, but now represents the probability that a limitation to UAM operations manifests as a response of annoyance. The function therefore is no longer a dose-response function, but rather is a mapping of noise dose to community acceptance constraint severity. Finally, just as the annoyance influence factors shifted the dose-response function, the identified public action factors also shift this new dose-constraint severity curve. The direction of impact on the function for a few of the key public action factors from Table III are presented in Fig. 19.

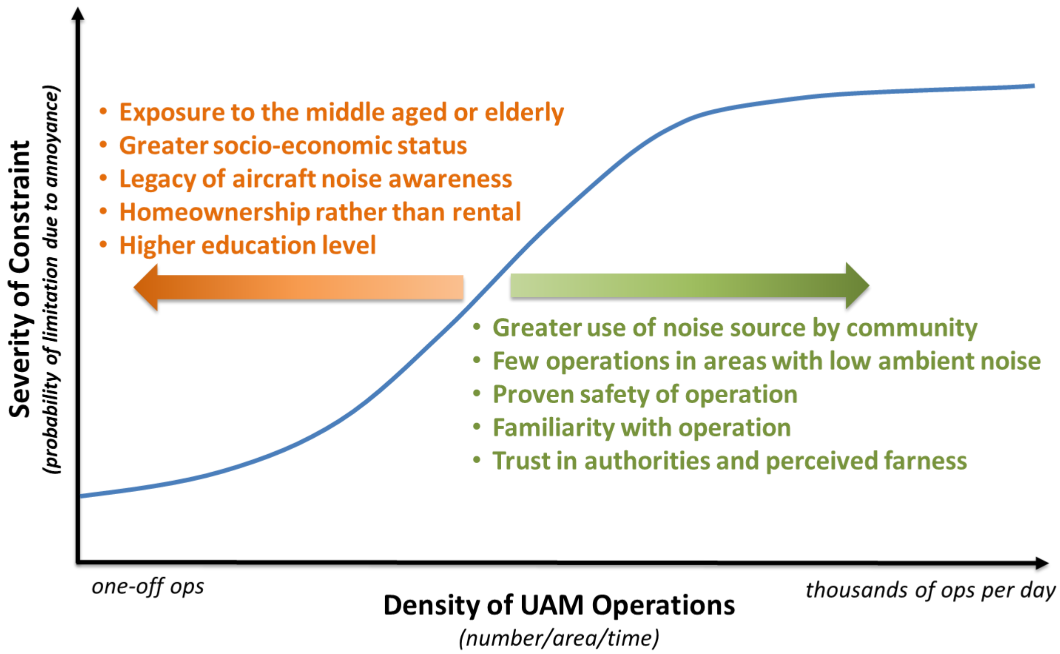

Fig. 19 Effect of the most significant public action influence factors on the notional dose-constraint severity function.

VI. Conclusion

Urban Air Mobility systems are rapidly evolving as numerous entities design and prototype new aircraft, low altitude air traffic control systems, and aviation business models. However, previous research has identified three key scaling constraints that may limit the implementation or growth of UAM systems. These constraints are the scalability of air traffic control systems in low altitude urban airspaces, the availability of ground infrastructure to support UAM operations near areas of customer demand, and the avoidance of community acceptance limitations as a result of noise generated by UAM operations.

The potential system scale, or number of operations that a UAM system could conduct during a given period, is one of the most important metrics to be estimated and understood during the conceptual design of a transportation system. Potential UAM operators need to understand achievable system scale to ensure their business plan closes. Aircraft manufacturers must anticipate system scale to properly amortize research and development investments and plan production capacity. Transportation planners and city governments must understand system scale to enable effective modeling and identify how UAM may be used effectively in a region. Finally, the FAA must understand UAM system scale to make proper investments in ATC capabilities to support it.

As proposed within this paper, the ultimate scale of a UAM system is dependent upon three key operational constraints. The severity of each constraint was shown to depend upon a number of *mechanisms* and dozens of fundamental technology, policy, operational, or societal *influence factors*. This research developed an influence diagram of each constraint to clearly identify the relation of these various factors to the constraint. Furthermore, an effort was made to relate UAM system scale to the resultant severity of each constraint and display how this relation changes in response to the mechanisms.

The *capacity* of an airspace sector was proposed as the key feature of the ATC scalability constraint. Capacity refers to the number of aircraft operations that can be simultaneously supported in a sector. Sector capacity was determined to be dependent upon three primary mechanisms, namely the separation minima in use, the design of airspace and routes, and the workload of controllers and pilots. Average delay experienced by operations was presented as a measure of ATC constraint severity.

The *geographic proximity to demand* and *throughput capacity* of a takeoff and landing area (TOLA) were determined to be the two key features of the ground infrastructure availability constraint. The geographic proximity of a TOLA refers to the ability to physically locate a TOLA in desired areas. It was found to be influenced primarily by mechanisms concerning development limitations (during siting, design, and construction) and regulations.

Throughput capacity refers to how many aircraft can arrive or depart from a TOLA in a given period. It was found to depend upon both the mechanisms from geographic proximity as well as mechanisms concerning aircraft handling, passenger handling, and operational limitations. Similar to ATC scalability, average delay experience by operators was also presented as a measure of ground infrastructure availability constraint severity.

The community acceptance of aircraft noise constraint was especially challenging to attempt to represent with a single metric and influence process. This research proposed a two-staged approach to understanding scalability limitations due to community acceptance. First, the *percentage of individuals highly annoyed* in a community was determined to be a salient metric for community acceptance. Annoyance was found to be subject to five mechanisms describing the acoustic, secondary effect, privacy, listener, and situational properties of the aircraft operation. Second, the *probability that an operational limitation is created* was proposed as a salient metric to capture the conversion of poor community acceptance to actual limitations for UAM operations as a result of public action. This metric was shown to be dependent upon political or legal action pathways and a few influence factors were proposed, however a detailed identification of mechanisms was not conducted for public action in this research.

Future efforts shall focus on leveraging the influence diagrams developed in this research to estimate probable, potential, and preferable UAM system scale scenarios in various cities and environments. Furthermore, the role that new technologies, ConOps, regulations, policies, and public outreach may play in realizing each scenario shall be investigated.

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