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Analysis of Urban Air Mobility Operational Constraints

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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. This paper investigates potential operational constraints that could arise during the implementation or scale-up of a UAM system. Literature on helicopter passenger networks was reviewed to determine operational constraints experienced by prior services similar to UAM. A constraint analysis was applied to near-term UAM operations in Los Angeles, Boston, and Dallas to assess if the historical constraints persist, or if novel constraints have emerged. The three city cases represented geographically diverse implementation regions for UAM services. A notional door-to-door concept of operations was applied to 32 reference missions within the three city cases. The reference missions exhibited a variety of requirements in terms of flight distance, passenger volume, market type, population overflight, and air traffic congestion, among others. By reviewing ground and flight operations for each reference mission, eight operational constraints were identified that could limit UAM system growth potential or prohibit UAM services altogether. The three most stringent constraints concerned community acceptance of aircraft noise, takeoff and landing area availability, and air traffic control scalability.

I. Introduction

URBAN air mobility (UAM) is a concept that proposes to develop short-range, point-to-point transportation systems in metropolitan areas using vertical takeoff and landing (VTOL) or short takeoff and landing (STOL) aircraft to overcome increasing surface congestion. While previous UAM endeavors provided helicopter-based passenger services, these did not achieve long-term viability due to issues such as fatal accidents, noise restrictions, and financial challenges. However, proponents of UAM anticipate that advancements in electric aircraft, automation, and telecommunications driven by unmanned aircraft system (UAS) and automobile applications may mitigate these challenges by 2020 [1,2].

The purpose of this analysis was to investigate the concept of operations (ConOps) for UAM systems in numerous settings, markets, and missions in order to identify potential operational factors that could constrain the implementation or scale-up of such a service. This analysis supports the development of appropriate requirements for both vehicles and operating networks.

An exploratory analysis of potential UAM systems was conducted in three case study cities. A notional mission profile for a generic UAM operation was applied to a series of reference missions within each city case. The reference missions represented a variety of markets and flight trajectories that may be served in near-term UAM implementation. Through an evaluation of hypothetical UAM operations for each reference mission by the authors, constraints were identified that may limit the implementation or scale-up of UAM services. These constraints were reviewed by subject matter experts to support their derivation and assess their severity. An analysis of 32 reference missions from the three city cases provided insight into how commonly the operational constraints appeared and how they related to specific mission types or environments. The identified constraints were compared with operational issues experienced in prior helicopter transportation networks.

II. Background

The UAM concept has been pursued in research and operation through numerous efforts since the 1950s. Although each iteration brought innovations in technology, business models, and target markets, the fundamental mission profile for the service has remained relatively consistent.

A. Historical Helicopter Transportation Systems

The first commercial helicopter air transportation company carried commercial passengers in 1953 to and from New York City's three major airports and into Manhattan beginning in 1956. Within a decade scheduled helicopter carriers were also operating in Los Angeles, San Francisco, and Chicago. Operations grew from under 155,000 annual helicopter passengers in 1957 to over 1.2 million passengers in 1967 [3]. In addition to these scheduled urban air carriers, over 100 helicopter-based air taxi operators also emerged providing prebooked, charter transportation [4].

Despite initial success, these early UAM operators were ultimately forced to reduce or terminate services due to community acceptance issues, fatal accidents, and financial challenges. Concept studies at the time concluded that the success of UAM systems using helicopters or other VTOL aircraft was hindered by the following operational issues:

1) Availability of geographically distributed takeoff and landing areas [3,5,6]
2) Scalability of air traffic control (ATC) [3–5]
3) Community acceptance of noise [3–8]
4) Operational safety and reputation [3–5,8]
5) High direct operating costs primarily from maintenance, fuel, and crew [4,5,8]
6) Logistical issues due to insufficient customer booking and demand management systems [3–5]
7) Operating capabilities in inclement weather [3–5]

B. Subsequent Air Mobility Concepts

Concepts for UAM continued to be proposed after the 1960s and focused on new vehicle configurations such as civil tiltrotors. However, these systems were not implemented due to commercial viability concerns as well as operational issues concerning community acceptance of noise and ATC scalability [9].

In 2010 NASA began development of a new vision for an On-Demand Aviation (ODA) system that relied upon small electric

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Propulsion Architecture	Lift Regime: *Rotor-Lift*	*Powered-Lift*	*Winged-Lift*
Conventional Architecture	helicopter	tilt-thrust compound heli	fixed-wing
Distributed Electric	multirotor	tilt-thrust lift + cruise	blown-wing
Takeoff/Landing Profile	*VTOL*	*VTOL or STOL*	*STOL*

Fig. 1 Configuration families of aircraft potentially suitable for UAM missions.

aircraft and advanced autonomy to conduct operations within approximately 165 miles of a city center [10]. Leveraging electric aircraft technologies and ATC developments from the Personal Air Vehicle (PAV) and Small Aircraft Transportation System (SATS) programs of the previous decade, ODA research addressed operational [11–13], certification [14], and economic challenges [15–17] of the proposed systems.

The concept of UAM was expressed in an Uber white paper [2] in 2016 as UAS technologies became increasingly capable and electric VTOL (eVTOL) programs displayed technical feasibility. Uber designated infrastructure development as the most significant operational constraint. Pilot training/automation, certification, aircraft noise, aircraft charging, weather, ATC, emissions, and economics were also cast as potential operational constraints. Studies by NASA and MIT provided greater detail on these projected operational constraints [18,19].

C. Emerging eVTOL and STOL Aircraft

The emergence of viable full-electric and hybrid-electric propulsion systems for small aircraft has resulted in new opportunities for UAM operators [20]. Figure 1 presents the design space of vehicle configurations that have been considered for use in UAM systems where the six cells correspond to aircraft configuration families distinguished by their propulsion architecture, lift regime, and takeoff/landing profile. While each configuration family is associated with differences in aircraft performance, operating cost, certifiability, infrastructure requirements, and noise generation, this analysis attempted to remain vehicle configuration agnostic and identify potential operational constraints that may impact any or all of the configuration families.

III. Study Approach

The objective of this study was to identify operational constraints that could impact the implementation or scale-up of UAM services in the near- or far-term. The study approach was to conduct exploratory system-level analyses in three city cases: Los Angeles, Boston, and Dallas. Los Angeles was selected as a city case due to an expectation that it was uniquely suited as an early adopter of UAM because of its large consumer base, severe roadway congestion, extensive existing helipad infrastructure, and mild weather. Boston and Dallas were chosen in order to evaluate UAM performance in regions with different geographic structure, demand patterns, and weather.

The case studies reviewed airborne and ground-based operations by first identifying the region in each city where UAM operations could likely be provided. Next, market analyses were conducted to determine the demand (routes, times of day, number of individuals, etc.) for UAM services in the city case. Based upon the identified markets, between 10 and 12 representative "reference missions" were defined per city case to represent diverse operational characteristics for the UAM system. A "day in the life" evaluation of a notional UAM ConOps was conducted for each reference mission and perceived operational challenges were documented. Finally, a comparative analysis of the identified operational challenges from the reference missions led to the definition of overarching operational constraints, which were compared with those identified in the literature.

A. Case Study UAM Boundary Definition

Four factors were evaluated to indicate where (geographically) UAM services were likely to be demanded within each of the city cases:

1) Commuter transportation flows into, out of, and within the metropolitan area

2) Current helicopter charter services and commuter airline routes to, from, and within the metropolitan area

3) Population density of communities in the region

4) Regions inaccessible through surface transportation (communities isolated by water bodies, for example)

These four factors enabled the identification of distinct mobility patterns, routes, and communities within each city case that jointly represented the geographic coverage area for potential UAM operations. The city case boundaries were drawn to include these mobility patterns as well as surrounding census tracts that had a population density of at least 101 people per square mile.

B. Case Study Market Analysis

Two potential UAM markets were considered for all city cases in the analysis:

1) *Daily Commute:* an aircraft is used during business days to transport individuals between a location near their residence to a location near their employment in the morning, and the reverse route in the evening.

2) *Noncommute Point-to-Point:* an aircraft is used to transport individuals on a noncommuter trip between two locations such as business trips between two companies, recreation trips to and from the city, or trips to sporting events, schools, airports, and hospitals.

While UAM services for law enforcement, news gathering, and package delivery may also represent UAM markets, missions of this type were not considered in this initial analysis as they were perceived to have smaller scaling potential and to be of less interest to near-term service providers. It was noted, however, that these services could influence UAM operations as they may have priority access to shared resources such as airspace and infrastructure.

Origin and destination (O-D) locations of significant travel demand in the city cases were identified for the daily commute and point-to-point markets. To characterize the geographic location and temporal variability of the demand, four specific consumer groups were identified that were likely to value high-speed UAM transportation despite higher relative service costs compared with ground modes. These consumer groups included individuals traveling long distances, through heavy congestion, with disposable income, or with tight arrival deadlines. The travel demand patterns for each of these four potential consumer groups were characterized through the review of census data, consumer wealth data, current helicopter and aircraft charter operations, and the identification of demand focal points within the city case.

C. Case Study Reference Mission Definition

A set of 10–12 representative UAM reference missions was developed for each city case. The missions were chosen to represent the potential breadth of system-level requirements that may emerge in each city concerning attributes such as mission range, ATC interactions, and the consumer group the mission would serve, among others. To this end, the reference missions of this analysis were not chosen to represent the largest market opportunities in each city, but rather were chosen to capture diversity in the market and mission profile requirements for UAM services.

Reference missions were defined by selecting O-D pairs from the identified consumer travel demand patterns. The total number of individuals traveling each daily commute reference mission route was determined from census data. Additionally, a surface transportation travel time profile was created for all the reference mission routes using Google Maps™ mapping service travel time predictions. This information provided insight into the likely high-demand periods for a UAM service as well as how many passengers each route may potentially be expected to accommodate.

Table 1 Notional mission ConOps for UAM

ConOps step	Description
Initiation	Customer submits a travel request
1	Aircraft preflight at staging area
2	Aircraft routed to the TOLA nearest to the customer origin
3	Customer takes ground transportation from origin to TOLA
4	Customer and aircraft are prepared for takeoff
5	Flight segment
6	Aircraft arrives at destination and customer disembarks
7	Customer take ground transportation to final destination
8	Aircraft turn (charging, cleaning, flight crew swapping)

In addition to these demand-based reference missions, a second set of reference missions was developed with randomly generated O-D pairs. It was anticipated that randomly defined missions may reveal unique mission profile characteristics and overcome selection bias inherent to the missions defined from current-day travel demand.

D. Reference Mission ConOps Evaluation

A notional ConOps that considered the actions of the aircraft, flight crew, support staff, and customers was drafted for each reference mission. The ConOps defined the set of possible activities completed from the time the customer ordered the service to shortly after the customer reached their destination. Table 1 presents a simplified mission ConOps that describes the phases of a generic UAM reference mission. In Table 1, the Takeoff and Landing Area (TOLA) refers to any location a UAM aircraft may depart from or arrive at.

The ConOps was applied to each of the reference missions to develop hypothetical mission timelines and identify potential operational challenges that may arise if the mission were attempted today. A challenge was defined as any situation that could negatively impact the feasibility of conducting of the mission. While some challenges were perhaps trivial in light of emerging technologies and proposed mitigation approaches, this research sought to be thorough in identifying the factors that could influence UAM operations.

E. Constraint Derivation and Consistency Analysis

The last step derived a set of overarching UAM operational *constraints* from the aggregated set of *challenges* identified in the reference missions. This was achieved by first mapping each of the challenges identified to the 32 reference missions. The mapping displayed which challenges consistently appeared throughout all the missions, which challenges were associated with factors unique to a specific city case or mission type, and which challenges were relatively rare and only appeared in a few missions. The challenges were then grouped according to common attributes (such as an influence on infrastructure or ATC) to derive a set of systems-level constraints. The constraints succinctly represent the crucial operational hurdles for UAM system implementation or scaling as experienced in the reference missions. Subject matter experts reviewed the proposed constraints to assess their applicability beyond the reference missions and the severity of their potential impacts.

The operational constraints derived from the reference missions were compared with those experienced in prior helicopter transportation systems. This final analysis provided legitimacy to the derived UAM operational constraints and insight into how new ConOps and technologies proposed for UAM systems may influence the manifestation of the historical operational issues.

IV. Case Studies

A summary of the results from each step of the approach for the Los Angeles, Boston, and Dallas city cases is presented below. Select examples are included to illustrate how the operational challenges were identified during the review of the notional UAM ConOps.

A. Definition of City Case Boundaries

The three cities displayed significant variability in their size and layout. The Los Angeles metropolitan region was polycentric in structure with numerous interconnected city centers spanning outward up to roughly 100 miles from the central business district. The total population of the Los Angeles metropolitan area was the largest of the cities studied. The Boston metropolitan area was considerably more centralized with nearly all densely populated communities and neighborhoods located within roughly 30 miles of the primary city center. A number of satellite cities were located roughly 40 miles from the Boston city center. Dallas and Fort Worth resided at the center of a populated area that extended out radially for roughly 50 miles. Figure 2 presents a population density map of the three city cases and displays the UAM system boundaries defined for each city case as a black polygon.

Two distinct mobility patterns potentially well-suited for UAM services were identified in each city case. First, "journey to work" commuter data from the U.S. Census Bureau's 2006 to 2010 American Community Survey (ACS) revealed high-volume transportation corridors between the city centers, outlying commuter communities, and suburban residential areas. These corridors were characterized by a relatively large number of commuters completing geographically similar routes on a daily or weekly basis.

The second mobility pattern was identified from existing helicopter charters, commuter airline operations, and market analysis and consisted of trips between points of interest such as to or from international airports, sports venues, tourist attractions, hospitals, schools, and recreational areas. Trips of this demand type represented a more diverse set of potential origin and destination points compared with the relatively well-defined corridors of the commuter missions.

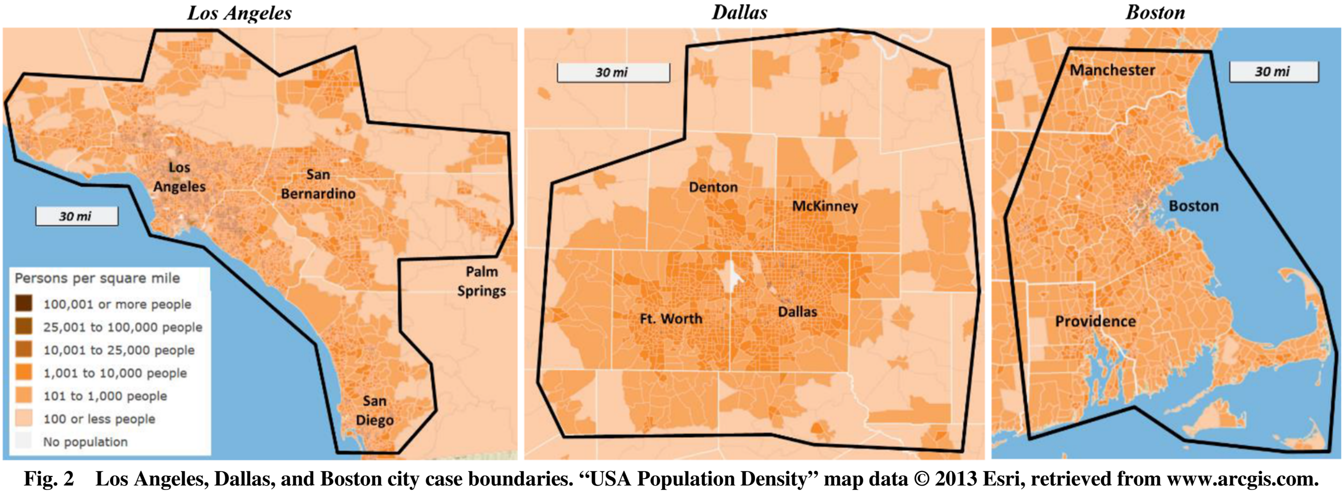

Fig. 2 Los Angeles, Dallas, and Boston city case boundaries. "USA Population Density" map data © 2013 Esri, retrieved from www.arcgis.com.

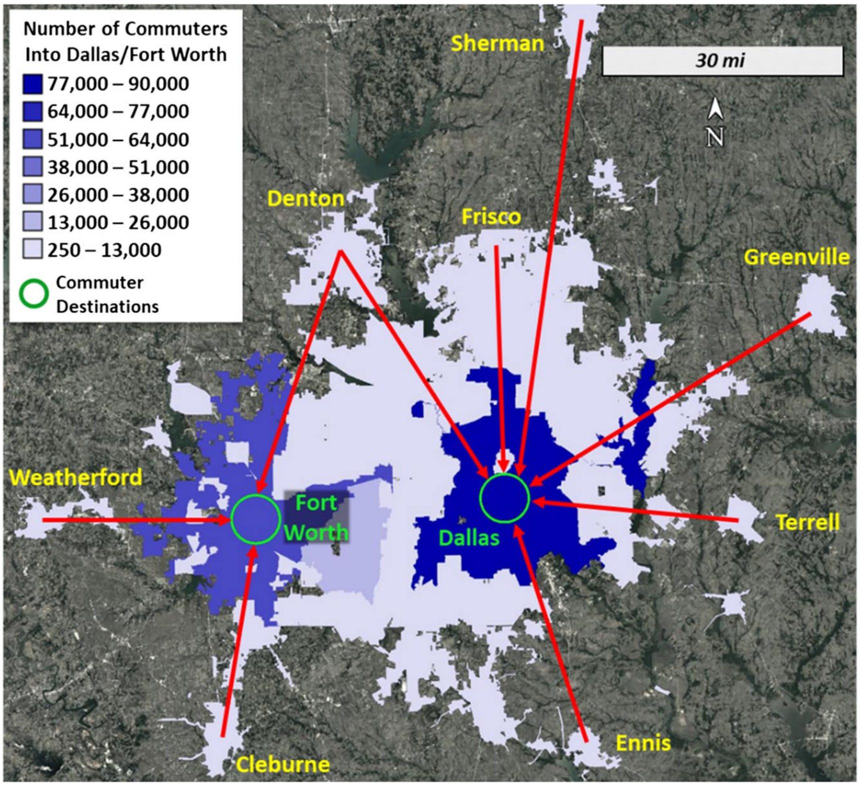

Fig. 3 Heat map displaying commuter flows from outlying communities into Dallas-Fort Worth. © 2017 *Google, Map Data: Landsat/Copernicus. Travel Data: U.S. Census Bureau OnTheMap*.

B. Consumer Demand Estimation

This research characterized travel demand patterns within each city case by examining the following:

1) *Census data* from the ACS 2014 Longitudinal Employer-Household Dynamics O-D Employment Statistics (LODES) were examined to identify communities experiencing long-distance commutes.

2) *Consumer wealth data*, gathered through the proxy of home valuation and average household income, were examined to identify high-income or wealthy communities.

3) *Current helicopter charter and commuter airline services* were reviewed to identify existing intercity air transportation routes and hubs.

4) *Demand focal points*, including public event venues with capacities greater than 15,000 people, nearby city centers, transportation hubs (public airports, train stations, and subway stations), notable tourist areas, and hospitals with more than 100 beds, were considered.

Analysis of the LODES census data sets supported the identification of roughly 10 "commuter communities" in each of the three city cases that resided outside the central metropolitan district and from which individuals commuted into the central district for work. At least 2000 individuals for Dallas, 4000 individuals for Boston, and 10,000 individuals for Los Angeles were reported to complete the trip from each commuter community for their primary employment. Figure 3 is a laborshed heat map that displays the number of commuters who travel from outlying communities to within three miles of the Fort Worth and Dallas city centers for work. It should be noted that the development of a viable UAM system may "induce" new demand and increase the number of long-distance commuters.

High-income communities were characterized either as contiguous census block groups with average household income of at

Table 2 Reference mission characteristics for the Los Angeles case study

Reference mission	Ground distance, miles	Line-of-sight distance, miles	Automobile travel time: Off-peak, min	Automobile travel time: On-peak, min	Congestion penalty, %
Daily commute missions					
1. Malibu to Century City	27.5	23.0	45	82	82
2. San Bernardino to Glendale	44.0	39.6	52	117	125
3. Antelope Valley to L.A. City Center	61.5	43.2	82	110	34
Point-to-point missions					
4. San Diego to L.A. City Center	122.0	111.0	125	195	56
5. LA City Center to Long Beach	26.5	20.8	35	77	120
6. Beverly Hills Hotel to LAX	13.0	9.5	30	67	123
7. Redondo Beach to Dodger Stadium	22.7	17.9	37	95	157
8. Rancho Palos Verdes to Hospital	8.5	5.3	18	23	28
9. San Marino to Palm Springs	116.0	99.5	125	185	48
Randomly generated missions					
10. San Bernardino to Perris	26.0	18.8	34	70	106
11. Arleta to Corona	71.0	60.2	92	190	107
12. Altadena to Culver City	30.0	21.2	58	130	124

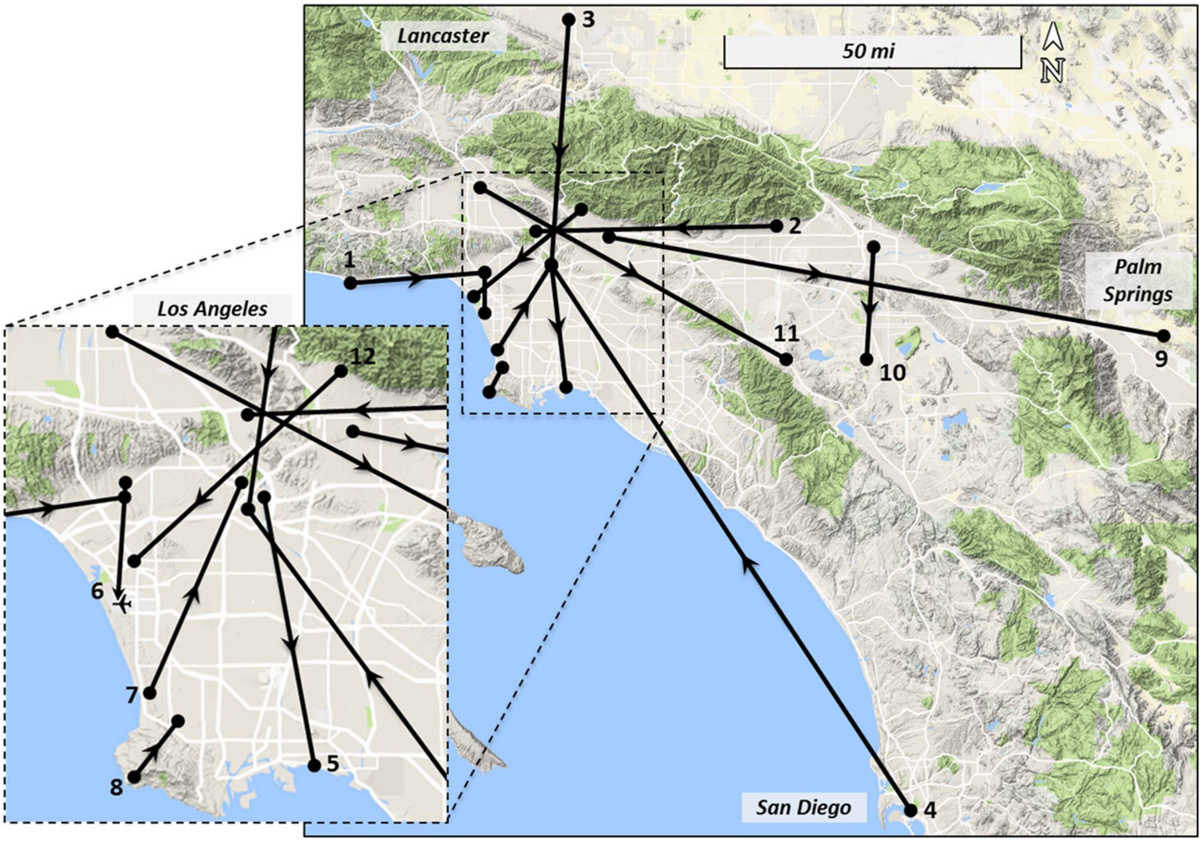

Fig. 4 Line-of-sight flight trajectories for UAM reference missions in Los Angeles. Map Data © 2017 Google, INEGI.

least $200,000, or as neighborhoods with average home valuations of greater than a threshold value chosen for each city. A valuation threshold of 1 million dollars was used for Los Angeles and Dallas, whereas a valuation threshold of $900,000 was used for Boston to capture differences in the housing markets.

When combined with a listing of demand focal points in each city (event venues, transit hubs, hospitals, etc.) and the current helicopter charter network service locations, the identified high-income and commuter communities formed the set of potential locations (O-D pairs) from and to which the UAM reference missions were defined.

C. Reference Missions Definition

Using the list of customer O-D pairs, daily commuter and point-to-point reference missions were developed for the three city cases. The missions were designed to represent a diversity of system-level requirements in each city including mission range, ATC interactions, and O-D locations. Through random O-D pair generation additional reference missions were defined.

The 12 reference missions defined for the Los Angeles city case are summarized in Table 2 and plotted in Fig. 4. The missions were on average longer than those of the other two cities due to the expansiveness of the southern California metropolitan area. Many of the Los Angeles missions also overflew mountains that acted as geographic barriers that increased the ground transportation distance compared with the line-of-sight distance for the missions. Furthermore, 7 of the 12 reference missions exhibited a congestion penalty of greater than 100%. The congestion penalty was the ratio of the average travel time during peak congestion periods to the average unimpeded travel time during free-flow conditions. A congestion penalty greater than 100% implies surface travel during the rush hour period required on average more than double the free-flow travel time.

Table 3 and Fig. 5 summarize the 10 reference missions defined for the Boston city case. A majority of the routes exhibited congestion penalties around 100%, indicating significant peak-hour congestion on the roadways. In contrast to Los Angeles' mountains, many of

Table 3 Reference mission characteristics for the Boston case study

			Automobile travel time		
Reference mission	Ground distance, miles	Line-of-sight distance, miles	Off-peak, min	On-peak, min	Congestion penalty, %
		Daily commute missions			
1. Providence to Boston Seaport	46.2	36.4	57	112	96
2. Waban to Prudential Center	10.2	7.3	14	35	150
3. Lexington to MIT	12.7	9.7	30	57	90
4. Hull to Financial District	21.4	10.2	42	92	119
		Point-to-point missions			
5. Harvard to Martha's Vineyard	88.6	70.2	150	210	40
6. Chestnut Hill to TD Garden	9.1	5.8	24	47	96
7. Wellesley to Logan Airport	20.6	15.3	32	60	88
8. Manchester-by-the-Sea to Harvard	33.5	22.9	45	87	93
		Randomly generated missions			
9. Dorchester to Cambridge	7.0	5.4	21	42	100
10 West Roxbury to Belmont	10.1	7.7	28	47	68

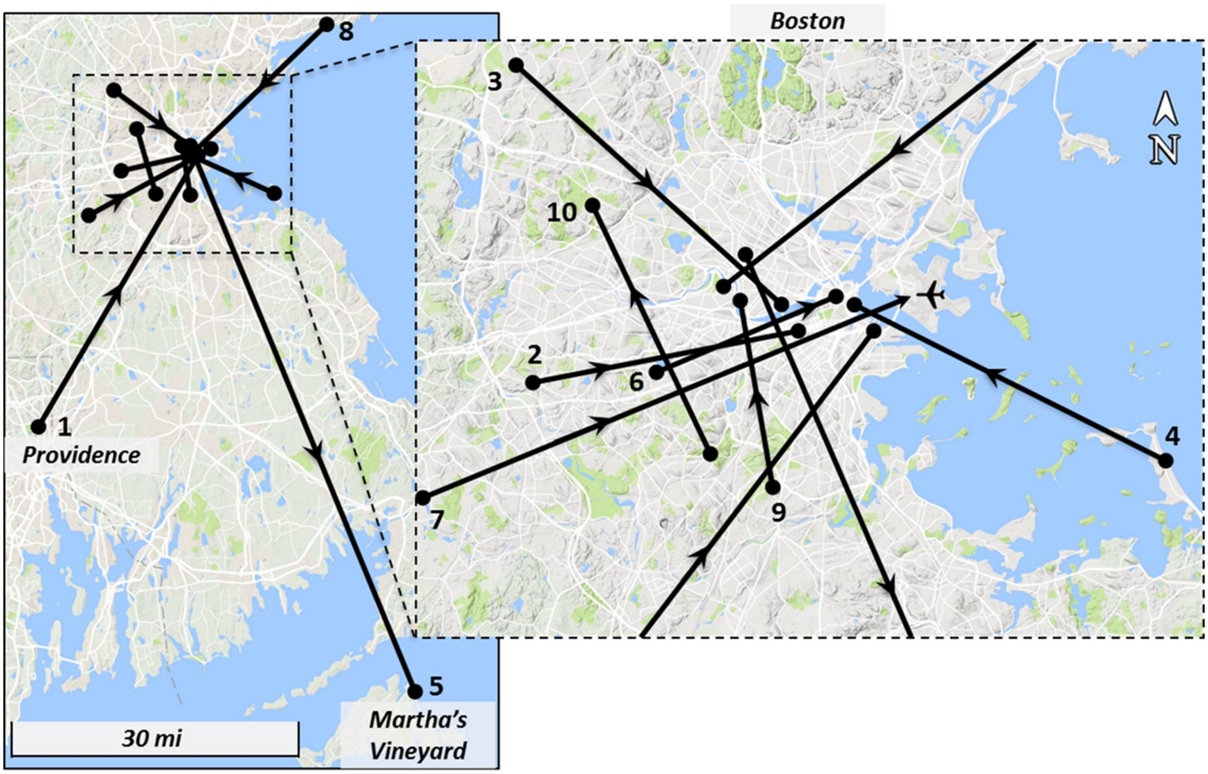

Fig. 5 Line-of-sight flight trajectories for UAM reference missions in Boston. Map Data © 2017 Google.

the Boston reference missions connected communities that were geographically separated by bodies of water and also exhibited large surface travel distances compared with their line-of-sight distance.

The 10 reference missions developed for the Dallas city case are presented in Table 4 and Fig. 6. The Dallas–Fort Worth metropolitan area exhibited relatively few geographic barriers to travel compared with the other two regions. Therefore, the primary potential advantage of air mobility in this market was not to significantly shorten the distance of travel compared with ground modes, but rather to overfly routes with high congestion penalties.

D. Demand and Travel Time Analyses

A consumer demand analysis was performed to assess the number of individuals currently conducting each daily commute reference mission. A surface travel time analysis was conducted for both types of reference missions to assess how the current driving time of each mission varied temporarily during a representative workday. An example of both analysis techniques is provided through a review of "Hull to Financial District" reference mission from the Boston case study.

Figure 7 displays the "inverse" laborshed mapping for Hull, where darker blue regions in Fig. 7 represent census tracts where more residents from Hull (highlighted in an orange polygon) traveled to for work to each day. While the largest number of commuters remained within Hull or the adjacent census tracts for their primary employment, a significant group of workers (329 according to the LODES data) also traveled to the financial district of Boston.

Figure 8 presents the ground transportation study for the Hull reference mission as well as the Beverly Hills Hotel to Los Angeles International Airport (LAX) reference mission. Ground transportation commuting times as predicted by the Google Maps™ mapping service were collected from 5:00 a.m. until 12:00 p.m. inbound from Hull to the Financial District, and from 1:00 p.m. until 8:00 p.m. on the reverse route. For the LAX mission, the expected travel times were collected inbound from the hotel to the airport for the entire study period.

Figure 8 displays a bimodal pattern for the Hull reference mission revealing the influence of the morning and evening "rush hour" periods of peak roadway congestion. The LAX mission, on the other hand, reveals only one period of significant roadway congestion in

Table 4 Reference mission characteristics for the Dallas case study

Reference mission	Ground distance, miles	Line-of-sight distance, miles	Automobile travel time		Congestion penalty, %
			Off-peak, min	On-peak, min	
Daily commute missions					
1. Frisco Square to American Airlines Center	26.6	25.0	31	58	87
2. Union Station to McKinney	33.6	31.2	40	78	95
3. Westlake to Dallas City Center	29.8	25.9	33	60	82
4. Fort Worth City Center to Union Station	31.7	30.5	35	45	29
Point-to-point missions					
5. DFW to Frisco Station	26.8	19.3	30	65	117
6. Union Station to DFW	18.9	15.9	23	36	57
7. Plano Station to Cowboys Stadium	38.6	29.5	40	65	63
8. Meacham Airfield to Texas Motor Speedway	19.3	14.6	25	36	44
Randomly generated missions					
9. Ferris to Irving	44.3	31.4	50	68	36
10. Mansfield to Plano	53.0	40.1	63	100	59

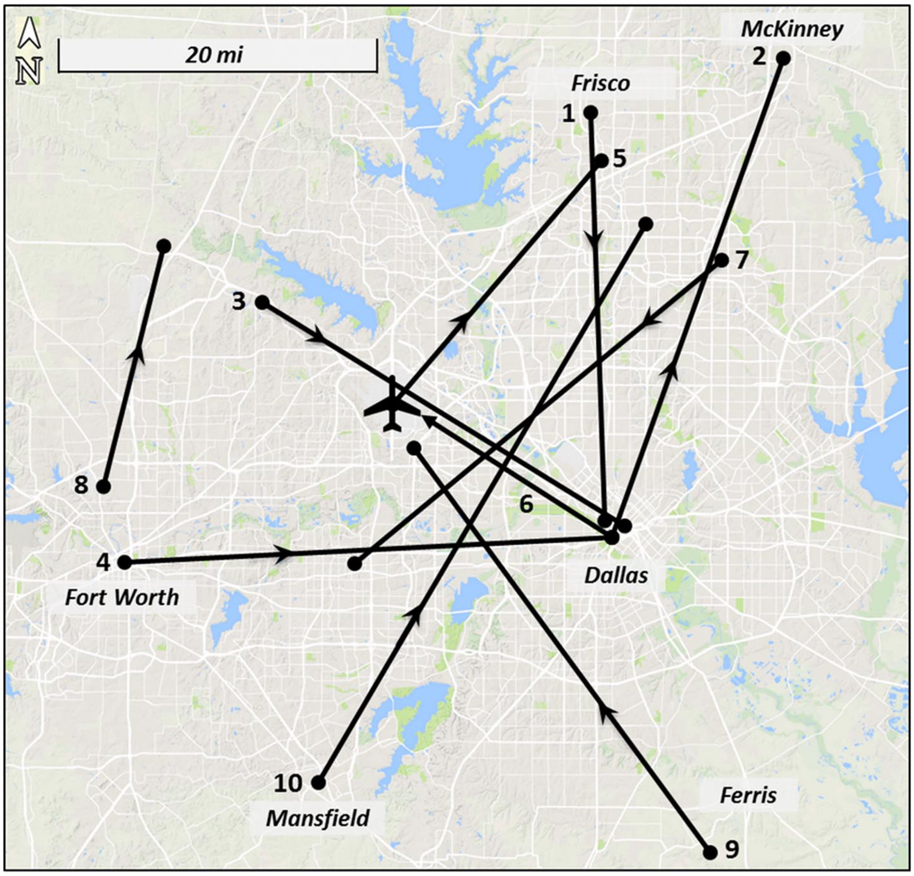

Fig. 6 Line-of-sight flight trajectories for UAM reference missions in Dallas. Map Data © 2017 Google.

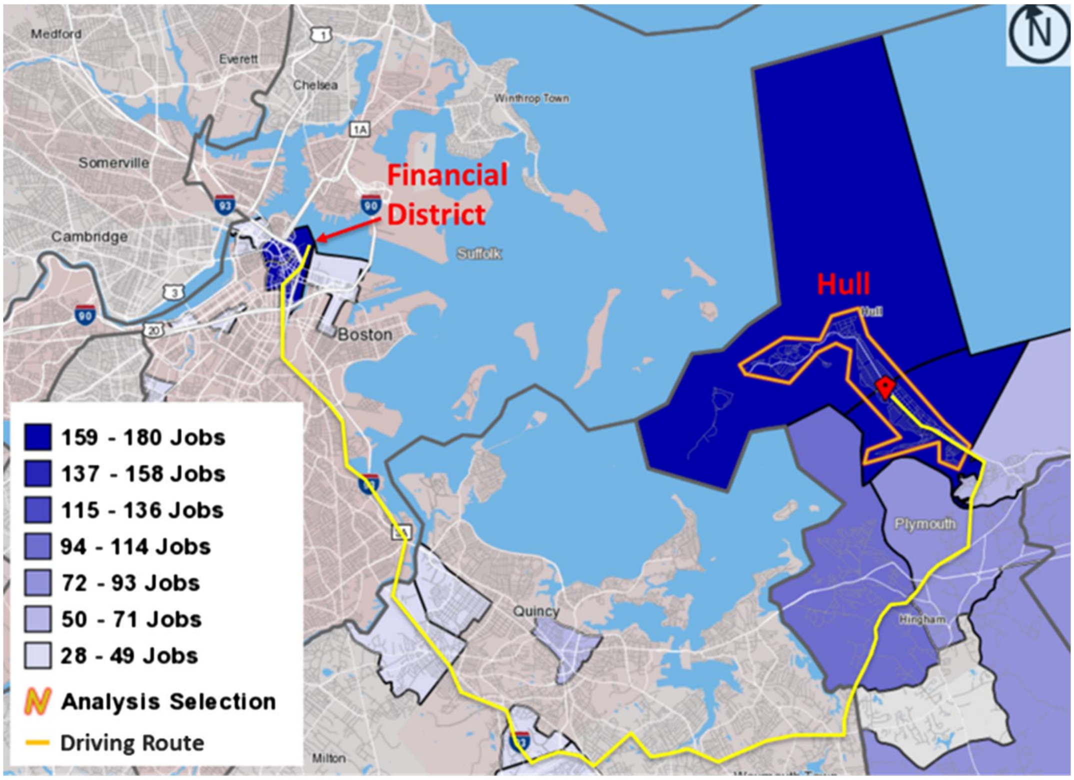

Fig. 7 Hull community (Boston) inverse laborshed map. Image developed with the U.S. Census Bureau OnTheMap application. http://onthemap.ces.census.gov/.

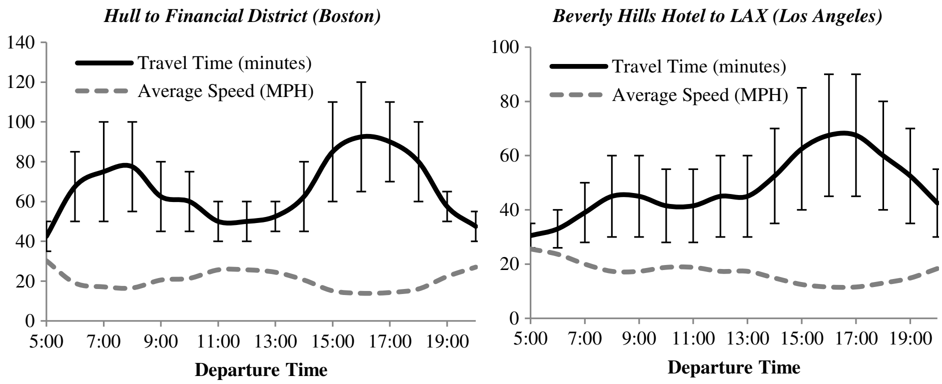

Fig. 8 Travel time and average speed distributions for two reference missions.

the evening as the travel direction during the morning was in the reverse commute direction. The travel time estimation error bounds are quite large during the peak congestion periods of the Hull mission and for nearly all periods of the LAX mission, indicating frequent and severe daily fluctuations in congestion for these reference missions. These error bounds represent the high and low travel time estimates provided by the Google Maps™ mapping service.

E. ConOps Evaluation and Challenge Identification

A step-by-step evaluation of the notional UAM ConOps was conducted for each reference mission to identify potential operational challenges. An operational challenge was considered to be a factor that could limit or prohibit throughput of UAM operations on a specified route. A walk through of each step of the generic UAM ConOps is provided with brief examples of how the identified operational challenges manifested in various reference missions. Each operational challenge identified is indicated with italicized text.

1. Aircraft Preflight

Before a UAM operation, a variety of preflight activities must be conducted to prepare the aircraft and crew for flight. Considering the actions that are required for preflight, *pilot staffing* and the impacts of *weather restrictions* were identified as potential UAM operational challenges.

First, adverse weather may reduce network reliability and performance by grounding aircraft or limiting airspace throughput. To evaluate to the first-order how frequently UAM system performance may be reduced in the three case study cities due to weather, data from METAR weather observations were collected from July 1, 2014, through June 30, 2017. Information on visibility, ceiling, winds, precipitation, temperature, and convective action was extracted from the reports. Figure 9 displays cumulative density functions (CDFs) for temperature and visibility in the three case study cities during the evaluation period. Visual flight rule (VFR) and special VFR (SVFR) visibility minimums, three SM and one SM respectively, are indicated within the visibility subplot.

Evaluation of Fig. 9 reveals that UAM downtime in Boston could be as much as 14% if aircraft had poor cold-weather performance. Boston and Los Angeles experienced visibility below the VFR minimums 6% and 4% of time, respectively. It was anticipated that instrument flight conditions would likely reduce or fully ground UAM system operations due to restrictive separation standards and requirements for enhanced equipage and pilot training. Boston and Dallas reported gusts above 20 knots 13% and 9% of the time, respectively, and Dallas reported convective action 6% of time, whereas Boston and Los Angeles reported convective action less than 1% of the time.

Pilot staffing was also identified as a potential operational challenge. Recent studies of the professional pilot supply pipeline correlated a decline in new pilots entering the U.S. market to international competition and a reduced rate of professional advancement [21]. Furthermore, the current maximum supply of pilots with private, commercial, or airline transport helicopter ratings in the United States is 6300, 25,700, and 4900, respectively, according to the FAA Airmen Certification Database. Because of the low number of existing helicopter pilots, the high demand for mainline airline aircraft pilots, and the large number of pilots needed for at-scale UAM operations (as many as 2000 pilots per city for Uber's 2025 UAM proposal), UAM operators may be challenged to hire sufficient pilots. Furthermore, unlike automobile ride-sharing, where drivers could quickly be acquired, pilot training for the commercial or airline transport certification is a time- and resource-intensive activity.

2. Aircraft and Customer Routed to Nearest TOLA

Once a customer travel request is submitted to the UAM system, an available TOLA near the customer must be selected as the pickup point. If an aircraft was not prepositioned onsite at the selected pickup TOLA, then one must be routed to the location from a nearby staging area or operation. Similarly, if the customer was not onsite then they also must take ground transportation for a "first mile" trip from their origin to the pickup TOLA. These two activities suggest that operational challenges may exist to develop a network of TOLAs that have sufficient *aircraft staging capacity* and *customer throughput capacity* and are in close *proximity to the customers' origin* points.

Figure 10 presents the type and location of the existing helipad and airport infrastructure within the three case study cities. Table 5 displays the number of facilities of each type. While all three cities contained a substantial number of TOLAs, the geographic distribution and throughput capacity of these facilities was found to be ill-suited for a majority of the reference missions. For 50% of the reference missions there was insufficient capacity to stage five or more aircraft at a facility

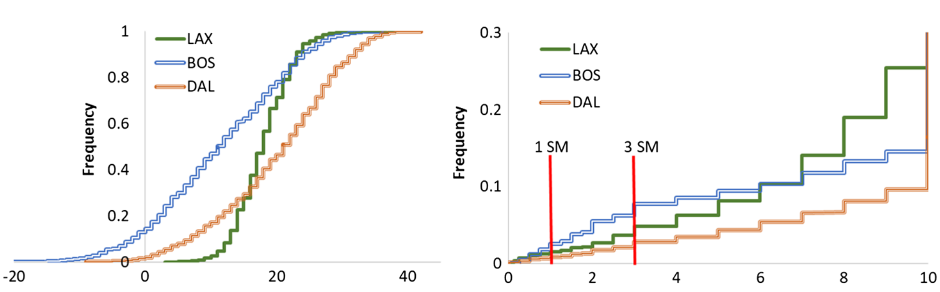

Fig. 9 Temperature and visibility characteristics for Los Angeles (LAX), Boston (BOS), and Dallas (DAL).

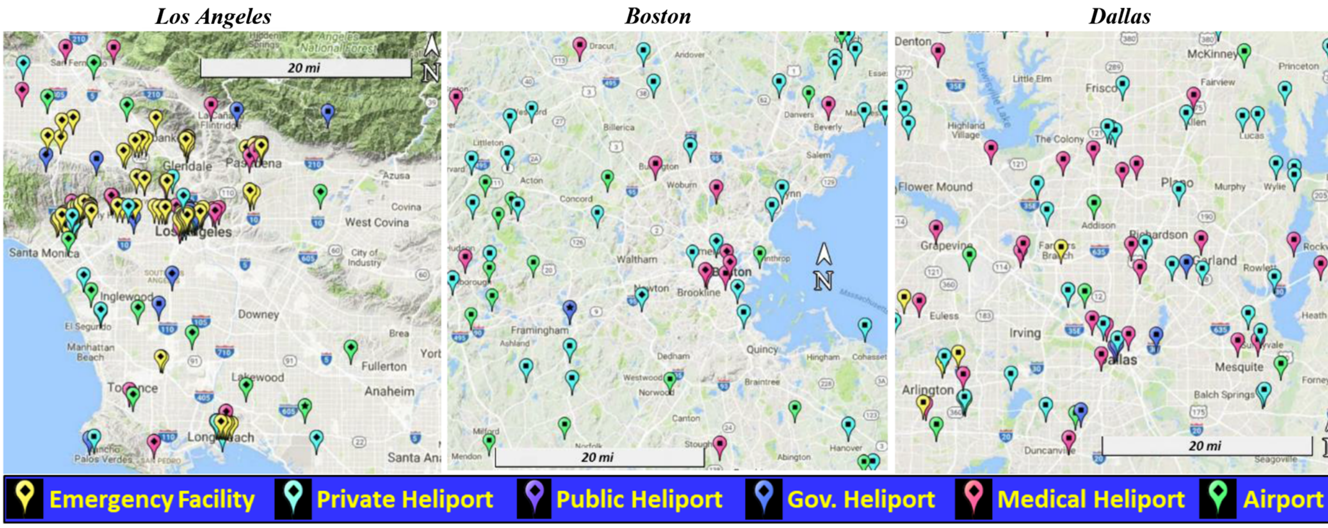

Fig. 10 Existing heliport and airport infrastructure in Los Angeles, Boston, and Dallas. ***Map Data © 2017 Google..***

within 5 miles of the pickup TOLA. Similarly, 38% of the reference missions did not have existing TOLAs close enough to the O-D points to limit the first mile and last mile ground transportation time to less than 30% of the baseline automobile travel time. In general, it was found that the existing TOLA infrastructure in Dallas was better suited to support UAM operations than the other cities due to more broadly distributed facilities and a high-capacity, public heliport located near the city center.

Because most current helicopter facilities can support only one vehicle at a time, low TOLA throughput could lead to congestion and issues of usage priority, especially if multiple operators use shared facilities. Similar to congestion at commercial airports in the air transportation system today, the lack of touchdown surfaces and loading pads (gates) could create congestion in a UAM system. Fifty-six percent of the reference missions operated to or from areas where there was a single TOLA that could only support a single operation at a time. Furthermore, the *integration of TOLAs with current ground transportation systems* (particularly the availability of automobile parking or customer drop-off areas) was identified as an operational challenge for 19% of the reference missions.

Finally, *regulatory compliance* with Title 14 of the Code of Federal Regulations (CFR)[§] Part 91, "General Operating and Flight Rules," and Part 135, "Operating Requirements for Commuter and On Demand Operations," was identified as a challenge for any UAM mission that may use electric propulsion technologies. Unlike airworthiness standards that may be certified by industry consensus standards under 14 CFR Part 23, Part 91 and Part 135 operating standards do not qualify for industry consensus at this time and may require regulatory changes or FAA approvals of equivalence between electric propulsion technologies and conventional propulsion technologies. For example, §91.205 requires aircraft be equipped with appropriate instruments and equipment to measure oil pressure, oil temperature, manifold pressure, and fuel level. Similarly, §91.151 and §135.209 set minimum break release fuel requirements for visual flight operations, and §91.167 and §135.223 set similar requirements for instrument flight operations. The certification of battery and engine management systems that calculate the required "minimum dispatch energy" and provide capabilities analogous to oil, manifold, and fuel sensors is therefore an operational challenge for the near-term use of electric aircraft.

3. *Customer Activities at TOLA*

Once the customer arrives at the TOLA a variety of activities may be necessary in order to prepare them and the aircraft for the flight. These activities include customer identity confirmation, a security scan (if necessary), customer escort to loading area, customer and baggage loading of aircraft, a preflight safety review, and aircraft startup, taxi, deicing, and takeoff.

Completing some or all of these tasks would require time, which would increase if there are no on-site personnel and the pilot must exit the aircraft (presumably shutting it down) to conduct the customer preparation activities. In either case, a potential operational challenge is the *duration of the aircraft occupancy time on the landing surface*. This challenge was projected to be especially limiting during peak congestion periods or at TOLAs that have only a single touchdown surface and few or no gate areas. Furthermore, surface transition for passengers who are elderly, disabled, young, or carrying luggage complicates the process and may add variability to the aircraft surface time.

Customer access to the TOLA and the *security of the TOLA and aircraft* were identified as two additional operational challenges. Seventy-eight percent of the reference missions used a TOLA that was located on a rooftop, inside a secure compound, on an airport, or in an area otherwise inaccessible to customers without an escort. Furthermore, all the reference missions used at least one TOLA that did not have on-site physical security or customer screening personnel. While it is unclear if security screening will be necessary for UAM operations, customers must be protected from hazards while accessing the aircraft and bystanders must be prevented from entering the area.

4. *Flight Segment*

The fifth step of the ConOps considered the departure, flight segment, and arrival of the aircraft. Numerous potential departure and arrival procedures and up to four potential flight trajectories were evaluated for each reference mission. Each trajectory was reviewed to identify required aircraft performance, ATC interactions, population overflight, and other conditions such as flight over open water. A majority of the flight trajectories used airspace up to 3000 ft AGL, although some longer-range trips reached up to 6000 ft AGL.

Table 5 Existing TOLAs by type in Los Angeles, Boston, and Dallas

TOLA type	Los Angeles	Boston	Dallas
Emergency helicopter landing facility	218	0	1
Private heliport	37	95	78
Government heliport	15	3	3
Medical heliport	24	41	53
Public use heliport	0	0	4
Airport	96	84	174

[§]All Title 14 CFR references in this paper were from the electronic Code of Federal Regulations, http://www.ecfr.gov [retrieved 7 November 2017].

The first challenge identified was *UAM aircraft interaction with ATC*. Flight through the various types of controlled and special use airspace places requirements on UAM operators concerning ATC clearance, equipage, and flight procedures. While in some cases UAM flight trajectories may be routed around controlled and special use airspace, 94% of the reference missions used a pickup or drop-off TOLA located within a surface-level class B, C, or D controlled airspace. These missions therefore required at a minimum communication with ATC to be completed.

While accessing controlled airspace is routine for operators today, as the number of UAM operations increases they will quickly reach flight densities that strain current ATC capabilities. The number and density of UAM operations anticipated by prospective operators exceeds by an order of magnitude the current number of commercial, general aviation, and helicopter flights that occur in terminal areas. For example, Uber has proposed to operate as many as 27,000 flights per day per metropolitan area by 2025. In comparison, the most active current helicopter market in the world is São Paulo, which supports a little over a thousand flights per day and is limited to six simultaneous operations in much of the airspace over the city due to controller workload restrictions [22]. UAM operations at proposed densities would be unsupportable with current ATC workload limitations, separation criteria, and voice communication protocols. Air traffic controllers may prohibit, limit, or delay UAM operations in specific airspace if flight congestion becomes too great [23].

A second operational challenge identified in the flight segment of the ConOps was the capacity for UAM operators to assure the *safety of high density flight operations occurring in uncontrolled airspace, especially airspace shared with UAS*. Currently, flight densities in most uncontrolled areas are relatively low; previous analysis of radar tacking data in Los Angeles suggested that the VFR corridors and Special Flight Rules Area (SFRA) above the city each accommodate only a few dozen helicopter and general aviation flights per day [24]. In convergence points where aircraft densities increase (such as above tourist landmarks or events), either ATC is responsible for providing separation or special operating procedures and communications frequencies have been established to support self-separation. For example, according to the New York City Economic Development Corporation, the Hudson River SFRA handles as many as 60,000 helicopter operations per year (a few hundred per day) without ATC support. However, as UAM and UAS operations surpass flight densities experienced in uncontrolled airspace today, the capabilities of pilots to effectively see and avoid other aircraft may be degraded.

Two additional operational challenges were identified specifically concerning the approach and departure phases of flight. Some TOLAs were identified to have *clearways where obstacles or procedures from nearby airports penetrated the approach and departure or transitional surfaces* of the TOLA. Access to these TOLAs may therefore be limited, require extended vertical flight segments, or require steep approach and departure angles. Extended vertical flight segments have also been proposed to be beneficial from a community noise and private-property overflight standpoint. The *safety of vertical flight segments* was considered an operational challenge because a majority of the proposed eVTOL aircraft are unable to effectively autorotate in the event of a common mode power failure, and existing ballistic recovery parachute systems do not operate at low altitudes and velocities [25].

The final flight segment operational challenge identified concerned *community noise exposure* from UAM operations. UAM aircraft are proposed to conduct frequent operations within communities that have traditionally been spared from airport noise. Fifty-six percent of the reference missions exhibited flight segments below 500 ft AGL over residential or tourist areas. Figure 11 displays how communities can limit aircraft operations through parallel pathways involving numerous stakeholders. Considering the degree of influence local communities have upon aircraft operations, UAM operators may face significant limitations from community acceptance of aircraft noise [22].

5. *Aircraft Arrival and Customer Last Mile Transport*

The aircraft arrival at the drop-off TOLA and “last mile” ground transportation of the customer exhibited many of the same operational challenges identified previously, including TOLA throughput, priority, and proximity; customer egress, safety, and security; and aircraft turn-time.

6. *Aircraft Transition to Next Operation*

The final step of the notional UAM ConOps was the preparation of the aircraft for another operation. The turn of a small, commuter aircraft may involve refueling, cabin cleaning, flight crew swapping, and replenishment of other consumables. Historical helicopter transportation networks and existing commuter airlines have displayed the feasibility of rapid aircraft turn-times as short as a few minutes. However, if UAM aircraft adopt hybrid-electric or full-electric architectures then new operational challenges concerning *battery charging* and *charging facility development* arise.

Customer demand for the commuter reference missions was highly directional with individuals traveling into the city centers during the morning peak period and returning to the residential areas during the evening peak period. The variance in demand between the peak and off-peak periods, as well as the directionality of travel in these periods, created a *geographic balancing* operational challenge where aircraft and pilots may accumulate in areas of low consumer demand. The impact of this challenge is to require nonrevenue “deadhead” flights to return aircraft from areas of low demand to high demand. As an initial order of magnitude estimate of this potential challenge for aviation, automobile ride-hailing networks have an estimated 20–50% deadhead ratio [26].

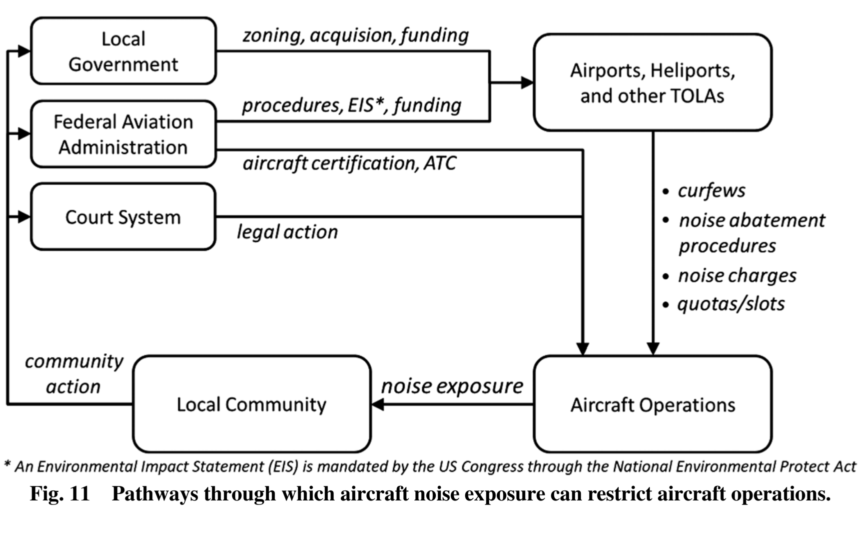

Fig. 11 Pathways through which aircraft noise exposure can restrict aircraft operations.

7. Results of the Reference Mission ConOps Evaluation

The 32 reference missions defined for the three city cases represented a diverse combination of flight trajectory, market demand, and infrastructure attributes. Table 6 presents a description of the key mission attributes and displays the range of attribute values evaluated in the reference missions.

Through the evaluation of the 32 reference missions, 19 potential UAM operational challenges were identified. The identified challenges are presented in Table 7 grouped by the mission ConOps step in which they manifest. Table 7 also presents the metrics used to determine if each operational challenge existed in a specific reference mission. Finally, Fig. 12 maps the operational challenges to each reference mission in which they were identified.

A few key trends were apparent from the mapping in Fig. 12. First, columns 11 and 12 display that only 2 of the 32 reference missions did not require access to surface-level controlled airspace. This indicated that interacting with ATC and gaining access to controlled airspaces would be a near-ubiquitous operational challenge for UAM systems.

Second, column 16 reveals that nearly all the reference missions required vertical flight segments to or from existing helicopter infrastructure. Only 4 of the 32 reference missions used a conventional runway at both the pickup and drop-off locations. This suggested that a UAM system seeking to leverage existing aviation infrastructure may be significantly limited if there are delays in the certification of aircraft with VTOL capabilities.

A third trend noticed is that 9 of the 19 identified operational challenges concerned TOLA (ground infrastructure) availability. Sixteen of the reference missions did not have existing facilities to stage five or more UAM aircraft within 5 miles of the pickup TOLA (column 3). Furthermore, numerous reference missions, including nearly all in Boston, did not have a TOLA located in close proximity to the origin or destination (column 6). Finally, the majority of existing TOLAs used by the reference missions in Boston and Los Angeles were located on private properties or rooftops, were not certified for public operations, and supported only a single aircraft. The various impacts of TOLA availability were therefore perceived as pervasive operational challenges for UAM systems.

A few other interesting trends were drawn from Fig. 12. For example, inclement weather conditions that may reduce UAM system performance were more common in Boston compared with the other two city cases (column 1). A majority of the reference missions in all three city cases used published helicopter or VFR corridors where they were more likely to interact with other air traffic (column 13). However, because the reference missions in this study leveraged existing heliport and airport infrastructure, all but four of the approach and departure clearways used by the reference missions were free of obstructions or interaction with other airport procedures (column 15). Finally, challenges related to pilot recruitment, regulations for minimum dispatch "energy" for electric aircraft, TOLA security and passenger screening, and aircraft charging stations were found to potentially exist in all reference missions.

Table 6 Attributes exhibited by the reference missions

Attribute	Description	Sampled range
Mission length	Line-of-sight mileage from origin to destination	7–111 miles
Surface congestion penalty	Ratio of peak congestion to free-flow surface travel time	28–157%
Population overflight	Population densities of census tracts under the flight path	0–100 K per miles^2
Airspace interaction	The number and types of airspaces entered along flight path	All classes
Infrastructure availability	Proximity of the O-D points to existing aviation infrastructure	On-site to 11 miles
Surface route efficiency	Ratio of surface route distance to line-of-sight distance	104–210%
High-income community	Household income or valuation above city-specific threshold	47% of missions
Arrival time deadline	Trip with a strict arrival deadline (e.g., airport, sporting event)	28% of missions

Table 7 Potential UAM operational challenges and reference mission evaluation metrics

Mission ConOps step(s)	Identified operational challenge	Reference mission evaluation metric (challenge exists in mission if metric evaluates positive)
Aircraft (A/C) pre-flight	1. Weather restrictions	1. Do convective weather, IMC, or subfreezing conditions occur during > 10% of the year?
	2. Pilot staffing	2. Potential challenge for all missions
Aircraft routed to nearest TOLA	3. Aircraft staging	3. Can ≤5 A/C be staged within 5 miles of origin TOLA?
	4. Dispatch regulations for electric A/C	4. Potential challenge for all missions
	5. TOLA throughput and use prioritization	5. Does either TOLA lack a second Touchdown and Liftoff (TLOF) surface onsite or within 0.5 miles?
First/last mile surface travel to/from TOLA	6. TOLA proximity to customer origin	6. Does the duration of first/last mile transport require >30% of the nominal non-UAM driving travel time?
	7. TOLA integration with ground transportation	7. Do TOLAs lack onsite public transit or parking?
Customer activities at TOLA	8. Customer physical access to TOLA	8. Are TOLAs in an area not accessible to the public?
	9. Aircraft occupancy time on TLOF	9. Does either TOLA have only one onsite TLOF?
	10. TOLA and aircraft security	10. Potential challenge for all missions
Flight segment	11. Access to controlled airspace	11. Does the flight use class B, C, D or special airspace?
	12. Autonomous aircraft interaction with ATC	12. Potential challenge for all flights in controlled airspace
	13. Safety of flight in areas of concentrated aircraft or UAS	13. Does the flight use an SFRA, helicopter, or VFR route?
	14. Community noise exposure	14. Does flight <500 ft occur in residential/tourist areas?
	15. Approach and departure clearways	15. Do approach/departure clearways contain obstructions or interact nearby facility procedures?
	16. Safety of vertical flight segments	16. Is a vertical flight segment required for the flight?
Aircraft transition to next operation	17. Aircraft charge time	17. Is mission range > 50 miles (extensive charging req.)?
	18. TOLA charging infrastructure	18. Does destination TOLA lack electric A/C chargers?
	19. Geographic balance of aircraft/pilots with demand	19. Is either TOLA > 25 miles from the primary city center?

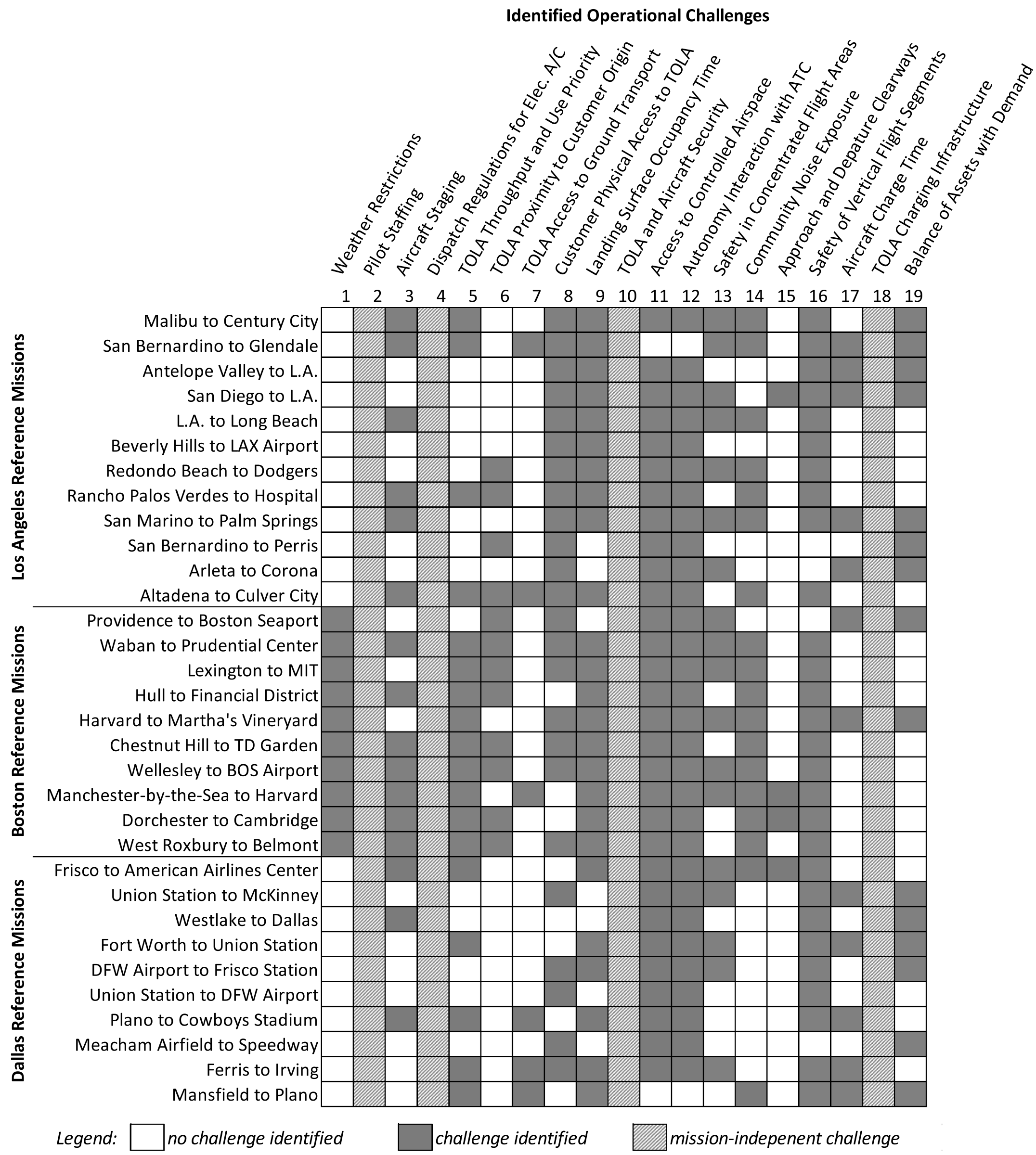

Fig. 12 UAM operational challenges identified through reference mission ConOps analysis.

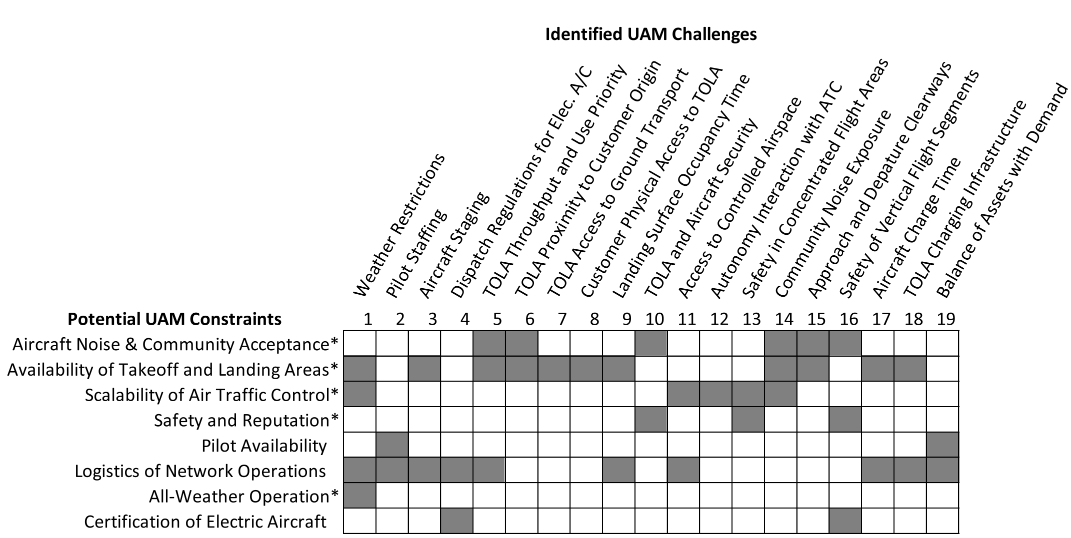

Fig. 13 UAM operational challenge to constraint mapping.

F. UAM Operational Constraint Derivation and Consistency Analysis

This research sought to decompose the 19 identified operational challenges into the fundamental constraints that influence UAM systems. The constraint derivation process was conducted by the authors and reviewed by experts in urban planning, transportation, piloting, airport development, and ATC. The experts were engaged through presentations or phone conferences to evaluate the severity of the challenges and assess how each could manifest as implementation or scaling constraints for UAM. Figure 13 lists the final eight potential UAM constraints derived through this process. The shaded cells indicate which of the 19 operational challenges identified in the case studies contributed to the definition of each constraint; the figure should be read from challenges to constraints and not vice versa.

An interesting observation from Fig. 13 is that some of the challenges influence multiple constraints. Perhaps the best example of this is the “community noise exposure” challenge (column 14). Aircraft noise directly influences community acceptance of the UAM system, but it also influences where TOLA infrastructure may be built and in some cases the approach and departure paths that ATC may assign. This is an important observation because it indicates that aircraft noise exposure may limit UAM services through three different constraint pathways. Similarly, inclement weather can constrain UAM systems either by grounding aircraft, reducing the capacity of airspace and ATC, forcing the temporary closure of TOLAs, or requiring significant re-routing and incurred delays.

Figure 13 also displays a consistency analysis to assess how the proposed UAM operational constraints compare to those experienced by previous helicopter transportation systems. Indicated as starred entries in the constraint column, five potential UAM constraints directly aligned with those presented in previous literature. The three identified constraints that did not correlate to those experienced by historical operators were determined to have emerged as a result of either changes in the state of the aerospace industry or as byproducts of new technologies.

V. Conclusions

This paper introduced three exploratory case studies that investigated potential operational constraints for urban air mobility (UAM). Nineteen operational challenges were identified that may impact the development, implementation, or operation of UAM systems in the near- or far-term. The challenges were determined through a review of the concept of operations for 32 reference missions projected to serve UAM markets in Los Angeles, Boston, and Dallas. Eight overarching UAM operational constraints were derived from the 19 identified challenges with the support of subject matter expert input. Five of these eight constraints directly corresponded to operational issues previously recognized by helicopter air carrier operators. The persistence of these constraints indicates that proposed UAM operations may continue to be hindered despite the availability of new technologies and business models.

Community acceptance of aircraft noise, takeoff and landing area availability, and air traffic control (ATC) scalability were perceived to be the operational constraints that were likely to cause the greatest scalability limitations for UAM systems. While the other constraints, such as the certification of electric aircraft operations, may also represent critical hurdles that must be overcome for UAM system implementation and scale-up, these three constraints were unique in that they impacted nearly all the reference missions regardless of differences in the cities and were not perceived to have a clear technical, operational, or regulatory mitigations.

The severity of each constraint, thought of as the limitation it may impose upon UAM operations, was dependent upon the number of UAM operations projected to occur in a geographic area. Some constraints, such as ATC, were not perceived to be active or “binding” for near-term UAM operations occurring at low flight densities but were likely to become binding as a UAM system scales.

The approach taken in this research was to present a systematic, first-cut analysis by exploring hypothetical UAM operations in three city cases, remaining vehicle configuration agnostic where possible, and drawing results and conclusions based upon general trends. However, because the case studies conducted in this research were focused solely on major U.S. metropolitan areas, the findings of this work are limited in their applicability. Metropolitan regions in different countries with different airspace management approaches or demand patterns may subject UAM operations to different constraints than those identified within this research.

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