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Final Report

Urban Air Mobility (UAM) Market Study

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National Aeronautics and Space Administration
Attn: Nancy Mendonca
Jonnelle Goff

SUBMITTED BY:
Booz Allen Hamilton
8283 Greensboro Drive
McLean, VA 22102

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TABLE OF CONTENTS

1.0 EXECUTIVE SUMMARY ... 6
2.0 INTRODUCTION ... 8
3.0 APPROACH ... 8
4.0 STRATEGIC ADVISORY GROUP (SAG): STRUCTURE AND ROLE ... 9
5.0 FOCUS MARKETS ... 10
6.0 FOCUS URBAN AREAS ... 14
7.0 LEGAL AND REGULATORY ASSESSMENT ... 20
7.1 Methodology ... 20
7.2 Legal and Regulatory Barriers ... 20
7.3 State and Local Regulatory Arena ... 22
7.4 International Regulations ... 25
7.5 Airworthiness Certification Standards and Regulations ... 27
7.6 Legal and Regulatory Summary ... 44
8.0 SOCIETAL BARRIERS ... 46
8.1 Literature Review ... 47
8.2 Focus Groups ... 50
8.3 General Population Survey ... 58
8.4 Societal Barriers Summary ... 72
9.0 WEATHER BARRIERS ... 75
9.1 Methodology ... 75
9.2 Results ... 79
9.3 Weather Barriers Summary ... 82
10.0 AIRPORT SHUTTLE AND AIR TAXI MARKET ANALYSIS ... 84
10.1 Design Mission and ConOps ... 84
10.2 Key Operations Related Assumptions ... 86
10.3 Price per passenger mile ... 87
10.4 Market Size and Value ... 93
10.5 Potential Externalities ... 97
10.6 Scenarios ... 100
10.7 Airport Shuttle and Air Taxi Analysis Summary ... 103
11.0 AIR AMBULANCE ... 105
11.1 Ambulance Mission and Scoping ... 107
11.2 Current Rotary Wing Market ... 109
11.3 Air Ambulance Mission and Assumptions ... 110
11.4 Cost per Transport ... 111
11.5 Scenarios: Revised ConOps and Battery Swapping ... 113
11.6 RW Market Size Capture ... 114
11.7 Air Ambulance Market Summary ... 117
12.0 LESSONS LEARNED AND RECOMMENDATIONS ... 118
13.0 APPENDIX ... 120
Appendix 1 – Societal Barriers (General Population Survey) ... 120
Appendix 2 – Weather Analysis ... 138
Appendix 3 – Market Analysis ... 145

LIST OF FIGURES

Figure 1: Overview of key challenges by market maturity and technology 7
Figure 2: High Level Approach for Urban Air Mobility market analysis 8
Figure 3: SAG Member institution type 9
Figure 4: Market selection criteria 12
Figure 5: Definition of Urban Areas and promise of Urban Air Mobility 14
Figure 6: Urban Area Selection Process 15
Figure 7: Weather Impacts 16
Figure 8: Focus Urban Areas 18
Figure 9: Trade-off between risk tolerance and level of certification rigor with FAA certification categories 29
Figure 10: NATO STANAG level of certification rigor increases with lower risk acceptance 29
Figure 11: International UAS regulatory field (Cuerno-Rejado, 2010) 30
Figure 12: Comparison for FAA and EASA Regulatory Framework Independence Metric 32
Figure 13: Paths to FAA airworthiness certification 34
Figure 14: Range of certification approaches for hybrid fixed wing and rotary aircraft 35
Figure 15: The type design approval process 36
Figure 16: Part 21.17(b) certification process 37
Figure 17: Sample means of compliance from Part 23 38
Figure 18: Sample results from the ASTM F38 standards gap analysis for UAS 40
Figure 19: UAM concept vehicles may fall along a spectrum ranging from resembling fixed wing or rotary aircraft 43
Figure 20: Research Process for Societal Barrier Studies 46
Figure 21: Survey responses to UAM familiarity 62
Figure 22: Willingness to fly among age groups 64
Figure 23: Perceptions of willingness and comfort 65
Figure 24: Perceptions of safety and security 66
Figure 25: Willingness to pay a premium fare to fly alone 68
Figure 26: Willingness to pay a premium fare by age demographics 69
Figure 27: Responses to UAM trip purpose 69
Figure 28: Perceptions from a non-user perspective 71
Figure 29: Surface and vertical sounding observation locations for 6 of the 10 target urban areas. Color shading area indicates spatial coverage of urban areas according to the U.S. Census 75
Figure 30: Distribution of PIREPs by weather condition at focus urban areas. No PIREPs were generated across our historical period in Honolulu 76
Figure 31: Average impact scores for each hour of UAM operational day at San Francisco urban area in summer 78
Figure 32: Hourly summer frequency of IFR conditions at LAX (orange) and VNY (blue) in Los Angles urban area 79
Figure 33: Hourly summer frequency of winds above 20 kts at SFO (orange) and OAK (green) 79
Figure 34: Modeling framework for Airport Shuttle and Air Taxi Analysis 85
Figure 35: Notional ConOps for Air Taxi and Airport Shuttle mission 86
Figure 36: Mission profile of Airport Shuttle and Air Taxi mission 86
Figure 37: Technical specifications of the vehicle types with uncertainty ranges; (top) Cruise Speed (mph) vs Range (miles), (bottom) Aircraft Price vs MTOW (lbs.) 88
Figure 38: Structure of Supply Economic Model for an eVTOL 89
Figure 39: Operating cost per passenger mile 91
Figure 40: Importance of operating assumptions 91
Figure 41: Operating cost breakdown 92
Figure 42: Price comparison with other modes of transportation 92
Figure 43: Structure of demand side model for urban air taxi 93
Figure 44: Total Daily trips in each urban area 93
Figure 45: Tradeoff between fidelity in results and computational speed 94
Figure 46: Step-by-Step Constraint application 95
Figure 47: Base year Demand comparison for focus urban areas 96

Figure 48: Price elasticity demand curve and revenue maximization. ... 96
Figure 49: Near-term Market Size and Value ... 97
Figure 50: Operations in Controlled vs Uncontrolled airspace ... 97
Figure 51: Percent of operations at different background noise levels ... 98
Figure 52: Well-to-wake greenhouse gas emissions comparison for eVTOLs ... 99
Figure 53: CO_2 emissions (well-to-wake) comparison of an eVTOL with Electric car ... 99
Figure 54: Framework for Scenario development. ... 100
Figure 55: Air Taxi and Airport Shuttle demand curve ... 102
Figure 56: Annual events by CMS Service Level ... 106
Figure 57: Typical Ambulance mission as defined by NEMSIS 2018 ... 107
Figure 58: Competition with Ground Ambulances ... 108
Figure 59: Ground distance for different service levels from dispatch to scene ... 108
Figure 60: Rotary Wing and Air Ambulance Bases in U.S. ... 109
Figure 61: Typical Air Ambulance mission ... 110
Figure 62: Structure of supply economic model for Air Ambulance ... 111
Figure 63: Cost per transport for eVTOLs and Hybrids ... 112
Figure 64: Breakdown of operating cost for different air ambulances ... 112
Figure 65: Scenario 1: Revised ConOps ... 113
Figure 66: Scenario 2: Battery Swapping ... 113
Figure 67: Comparison of total call time ... 114
Figure 68: Demand Model for Air Ambulances ... 114
Figure 69: Demand Distribution of RW Market by Hour and Day of Week Averaged over 2014-2016 ... 115
Figure 70: Dispatch protocol as per Emergency Medical Services 2015 ... 115
Figure 71: Dispatch Reliability of air ambulances ... 116
Figure 72: RW Market Capture Probabilities ... 117
Figure 73: Recent Trip Purpose ... 120
Figure 74: Most Recent Trip Distance ... 121
Figure 75: Most Recent Trip Mode ... 122
Figure 76: Commute Mode ... 122
Figure 77: Aircraft Exposure ... 123
Figure 78: Flight Frequency ... 124
Figure 79: Factors affecting Decision to Fly ... 125
Figure 80: Factors Affecting Flight Experience ... 125
Figure 81: On-Board Experience ... 126
Figure 82: Perceptions of Weather ... 131
Figure 83: Perceptions of Weather (cont…) ... 131
Figure 84: Security Screenings ... 132
Figure 85: Likely Travel Partners ... 132
Figure 86: AV vs. UAM Travel ... 133
Figure 87: SAV vs. UAM Travel ... 134
Figure 88: Willingness to Use Vertiport ... 135
Figure 89: Time to Access Vertiport ... 135
Figure 90: Cost to Access Vertiport ... 136
Figure 91: Time series of frequency of winds above 20 kts by season in Honolulu urban area. ... 138
Figure 92: Time series of median temperature in summer (top left), frequency of thunderstorms by season (top right), and frequency of winds above 20 kts by season (bottom left) in Phoenix urban area. ... 138
Figure 93: Time series of frequency of IFR conditions in summer at LAX and VNY (left) and in aggregate by season in Los Angeles urban area. ... 139
Figure 94: Time series of frequency of winds above 20 kts in summer at OAK and SFO (top left), station aggregate by season (top right), and frequency of IFR conditions in summer (bottom left) in San Francisco urban area. ... 139
Figure 95: Time series of frequency of thunderstorms by season (top left), frequency of IFR conditions by season (top right), and 5th percentile (blue line), median (purple line), and 95th percentile (red line) temperature by season (bottom) in Denver urban area. ... 140
Figure 96: Spatial distribution of PIREPs (left) and percentage of total reports by reported condition across historical period in Denver urban area. ... 140

Figure 97: Time series of frequency of thunderstorms in summer (left) and frequency of IFR conditions in summer (right) in Washington, D.C. urban area. 141
Figure 98: Spatial distribution of PIREPs (left) and percentage of total reports by reported condition across historical period in Washington, D.C. urban area. 141
Figure 99: Time series of frequency of winds above 20 kts in winter by METAR location (top left), frequency of IFR conditions by season (top right), and vertical distribution of wind speed during winter morning in New York urban area. 142
Figure 100: Spatial distribution of PIREPs (left) and percentage of total reports by reported condition across historical period in New York urban area. 142
Figure 101: Time series of frequency of IFR conditions by season (left) and frequency of thunderstorms by season (right) in Miami urban area. 143
Figure 102: Time series of frequency of IFR conditions in winter at HOU and IAH (top left), frequency of thunderstorms by season (bottom left), frequency of IFR conditions in aggregate by season (bottom right), and temperature statistics by season in Houston urban area. 143
Figure 103: Spatial distribution of PIREPs (left) and percentage of total reports by reported condition across historical period in Houston urban area. 144
Figure 104: Time series of frequency of IFR conditions by season (top left), frequency of thunderstorms by season (top right), median temperature in summer (bottom left), and vertical distribution of wind speed during fall at both 12Z and 00Z in Dallas urban area. 144
Figure 105: Technical specifications of select vehicles (source: eVTOL News) 145
Figure 106: Structure of Cost Modeling 146
Figure 107: Capital and Insurance Cost Model 146
Figure 108: Aircraft Price per Seat 147
Figure 109: Capital Cost per Passenger Mile 147
Figure 110: Insurance Cost per Passenger Mile 148
Figure 111: Energy Cost Model 148
Figure 112: Hover and Cruise power requirement (source: McDonald, R et al) 148
Figure 113: Energy Cost per Passenger Mile 149
Figure 114: Battery Cost Model 149
Figure 115: Battery Life Cycle and Capacity Dependencies 150
Figure 116: Battery Reserve Cost per passenger mile 150
Figure 117: Crew Cost per passenger mile 151
Figure 118: Infrastructure Cost Model 151
Figure 119: Infrastructure cost per passenger mile 152
Figure 120: Infrastructure cost per passenger mile 152
Figure 121: Route Cost per passenger mile 153
Figure 122: Indirect Operating Cost per passenger mile 153
Figure 123: Taxes and Fees per passenger mile 154
Figure 124: Weather Adjustments in a mission 154
Figure 125: Trip Production and Attraction process 155
Figure 126: Trip Share by Travel Time and Mode (source: ACS, 2016) 155
Figure 127: Qualifying Trips 156
Figure 128: VTTS uncertainty line 157
Figure 129: Infrastructure Capacity Constraint 157
Figure 130: Time of Day Restrictions 158
Figure 131: VFR conditions at each urban area 158
Figure 132: Market Share by Aircraft type for each Urban Area 159

LIST OF TABLES

Table 1: Potential UAM Markets 10
Table 2: Focus Markets 12
Table 3: International Type Certification Comparison 33
Table 4: Summary of key standards, gaps, and activities 41
Table 5: Focus Group Participant Demographics 51
Table 6: Five U.S. Metropolitan Regions Surveyed 58
Table 7: Willingness-to-Fly Scale 59
Table 8: Demographic Data 61
Table 9: Stated Preference Attributes 66
Table 10: Impact Scores for each weather condition from METAR 77
Table 11: Average seasonal density altitude for focus urban areas. 81
Table 12: Average number of weather impacted hours for all target urban areas by season 82
Table 13: Operations Related Assumptions for Monte-Carlo (first few years of service) 87
Table 14: Key Assumptions in each of the cost component 90
Table 15: Different Service Level as defined by CMS 105
Table 16: Crew Service Requirements 106
Table 17: Operations Related Assumptions for Monte-Carlo (first few years of service). 110
Table 18: Specifications of vehicles analyzed 111
Table 19: Initial Reactions 127
Table 20: Crosstabs on Socio-Demographic Variables 128
Table 21: Ordinal Regression Model 129
Table 22: Stated Preference and Willingness to Pay 130
Table 23: Preferred Modes for Vertiport Access 136

1.0 EXECUTIVE SUMMARY

The Booz Allen Team explored market size and potential barriers to Urban Air Mobility (UAM) by focusing on three potential markets – Airport Shuttle, Air Taxi, and Air Ambulance. We found that the Airport Shuttle and Air Taxi markets are viable, with a significant total available market value in the U.S. of $500 billion, for a fully unconstrained scenario. In this unconstrained best-case scenario, passengers would have the ability to access and fly a UAM at any time, from any location to any destination, without being hindered by constraints such as weather, infrastructure, or traffic volume. Significant legal and regulatory, weather, certification, public perception, and infrastructure constraints exist, which reduce the market potential for these applications to only about 0.5% of the total available market, or $2.5 billion, in the near term. However, we determined that these constraints can be addressed through ongoing intra-governmental partnerships, government and industry collaboration, strong industry commitment, and existing legal and regulatory enablers. We found that the Air Ambulance market is not a viable market if served by electric vertical take-off and landing (eVTOL) vehicles due to technology constraints but may potentially be viable if a hybrid VTOL aircraft are utilized.

The barriers and challenges we characterized in this study can be stratified according to their applicability or potential mitigation through technology as well as market maturity (Figure 1). In the near term, high cost of service will be a key economic challenge. We found potential for significant reduction in service cost through increased vehicle and component efficiency, and automation in a more mature market scenario. Weather conditions also pose a challenge to the UAM market, though there is potential for mitigation of some of these impacts through technology such as sensors enabling operations in low visibility. However, even in a mature market with advanced technology, disruptions are still likely to occur due to weather events such as thunderstorms and strong winds. High density operations will likely stress the current Air Traffic Management (ATM) system in the near term, but technology and new initiatives such as the Air Traffic Management -eXploration project (ATM-X) will enable safe and efficient integration of UAM into the National Airspace System (NAS). Current battery technology creates a barrier in the near term, especially for the Air Ambulance market, as battery weight and extensive recharging times would be needed for these operations. Advancements in battery technology, as well as use of hybrid VTOLs, could significantly reduce this barrier in the longer term. As UAM emerges as a viable mode of transportation in the near term, adverse energy and environmental impacts, particularly noise, may impact community acceptance and potentially persist as the market matures into larger-scale operations.

For non-technology related challenges, we found that infrastructure constraints will create a significant barrier to UAM in the near term but could be addressed in the longer term through development and expansion of vertiports. Competition from existing modes of transportation such as ride-sharing (e.g., Lyft, Uber) and ground taxi's pose a key barrier to UAM in the short term, which will likely evolve into competition from other emerging technologies such as autonomous cars and electric trains in the longer term. Weather events will influence other components of the operation such as passenger comfort (e.g., extreme temperatures, turbulence) and infrastructure (e.g., winter weather causing cracks and degradation in vertiports). There is also potential for these impacts to be heightened in the longer term from the increased frequency of adverse weather such as thunderstorms due to changing climatic conditions. We also found that the public has strong concerns about safety as a passenger in a piloted UAM, including "lasing" of pilots, unruly passengers, and sabotage. They would prefer that all passengers pass through a security screening process before boarding a vehicle. They would also prefer to use UAM for longer regional trips, such as flying from Washington, DC to Baltimore, MD or San Diego, CA to Los Angeles, CA. A longer term automated UAM vehicle market will face challenges due to public apprehension about automation and unmanned operations, and a preference to fly with passengers they know in an autonomous (unmanned) operational scenario.

	Near Term- Immature Market	*Longer Term- Mature Market*
Technology Challenges	**Economics:** High cost of service (partially driven by capital and battery costs) **Weather:** Adverse Weather can significantly affect aircraft operations and performance **Air Traffic Management:** High density operations will stress the current ATM system **Battery Technology:** Battery weight and recharging times detrimental to the use of eVTOLs for Air Ambulance market **Impacts:** Adverse energy and environmental impacts (particularly, noise) could affect community acceptance	**Impacts:** Energy and Environmental Impacts of large-scale operations **Cybersecurity** of Autonomous systems including vehicles and UTM **Weather**: Disruptions to operations during significant adverse conditions **New Entrants:** Large scale operations of new entrants like UAS, Commercial Space operations, private ownership of UAM vehicles could increase the complexity of airspace management and safety
Non-Technological Challenges	**Infrastructure:** Lack of existing infrastructure and low throughput **Competition:** Existing modes of transportation **Weather:** Conditions could influence non-technological aspects of operation **Public Perception:** Passengers concerned about safety and prefer security screening and preference UAM only for longer trips **Laws and regulations** for flying over people, BVLOS, and carrying passengers (among others) are needed **Certifications:** Gaps in the existing certification framework where UAM will experience challenges, particularly system redundancy and failure management	**Competition: E**merging technologies and concepts like shared Electric and Autonomous Cars, and fast trains **Weather:** Increase in some adverse conditions due to climate change may limit operations **Social Mobility:** New importance of travel time, increase in telecommuting, urbanization and de-congestion scenarios could reduce the viability of markets **Public Perception:** Passengers trust and apprehension with automation and pilot-less UAM and prefer to fly with others they know in an autonomous UAM

Figure 1: Overview of key challenges by market maturity and technology

2.0 INTRODUCTION

Urban Air Mobility (UAM) is an emerging concept of air transportation where small package delivery drones to passenger-carrying air taxis operate over populated areas, from small towns to the largest cities are being considered. This could revolutionize the way people move within and around cities by shortening commute times, bypassing ground congestion, and enabling point-to-point flights across cities. In recent years, several companies have designed and tested enabling elements of this concept, including; prototypes of Vertical Take-Off Landing (VTOL) capable vehicles, understanding of operational concepts, and development of potential business models.

While the UAM concept may be enabled by the convergence of several factors, there are several challenges that could prevent its emergence and sustainable development, including but not limited to: societal impacts and acceptance, economics and affordability, regulations and certifications, adverse weather conditions, competition with other modes, infrastructure requirements, air traffic management and pilot shortage.

There is a need to understand the potential market size of UAM and identify challenges to achieving a viable market, as well as how the constraints and challenges could impact the size and viability of this market. Therefore, the objective of this study is to understand and estimate the potential market size of UAM and identify legal, societal and other constraints to adoption of this rapidly emerging technology.

3.0 APPROACH

The Booz Allen team adopted a four-phase approach to understand the UAM ecosystem and performed a targeted deep dive on focus markets that highlighted significant barriers to realization. This approach is outlined in Figure 2.

- ***Scoping:*** In this phase, over 36 mission types were identified that can be potentially served by vehicles with Vertical Take-Off Landing (VTOL) capabilities.
- ***Initial Assessment:*** Three focus markets were selected. The assessment was centered on preliminary market analysis and evaluation of barriers (e.g., legal, societal, and economic).
- ***Interim Assessment:*** We refined our methodology and assumptions based on feedback from the Booz Allen UAM Strategic Advisory Group (SAG) and conducted a comprehensive analysis of the three markets.
- ***Final Assessment:*** The Booz Allen team documented lessons learned and recommendations.

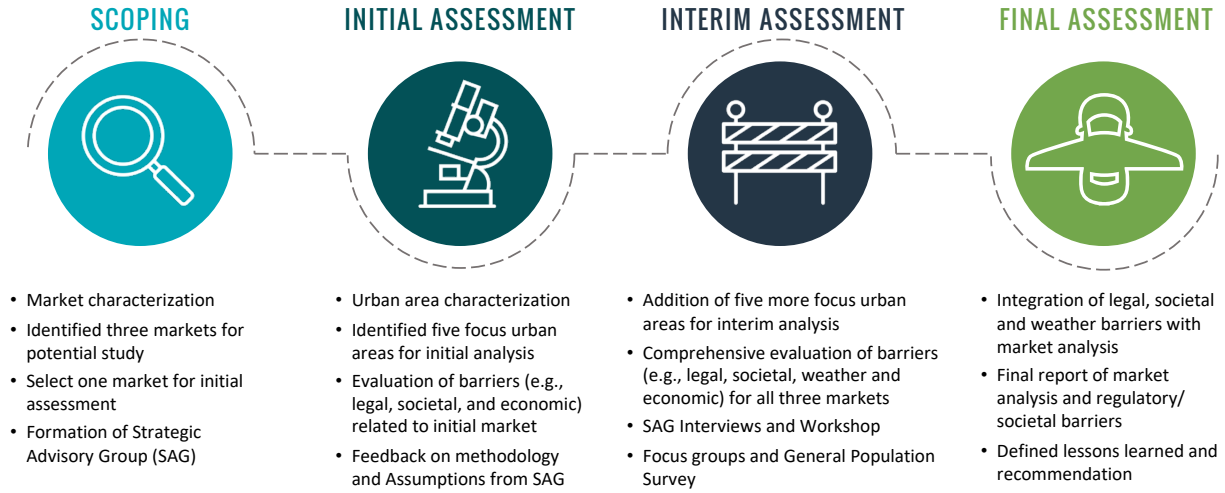

Figure 2: High Level Approach for Urban Air Mobility market analysis

4.0 STRATEGIC ADVISORY GROUP (SAG): STRUCTURE AND ROLE

UAM is an emerging concept that spans multiple industries and disciplines with substantial uncertainty. The Booz Allen team established the SAG to provide input and feedback on the approach, methodology, assumptions, and results. The SAG comprised of 51 diverse and independent individuals and groups of UAM and/or related market experts and stakeholders. They informed key decision points in this study and helped refine the market assessment methodology based on their expertise.

As shown in Figure 3, the SAG captured a wide and diverse range of stakeholders, including manufacturers, operators, research institutions, regulators at the federal, state and local level, venture capital, etc. In total, 35 organizations contributed including FAA (UAS Integration Office, Aviation Policy & Plans Office, Office of International Affairs, Office of Environment and Energy), the Volpe National Transportation Systems Center, International Civil Aviation Organization (ICAO), National Center for Atmospheric Research (NCAR), National Transportation Safety Board (NTSB), North Carolina Department of Transportation (NCDOT), New York City Taxi & Limousine Commission, Los Angeles City's Mayor Office, Pittsburg's Department of Mobility and Infrastructure, Los Angeles World Airports (LAWA), Smart Cities Lab, Hogan Lovells, Windels Marx LLP, Akin Gump Strauss Hauer & Field LLP, Massachusetts Institute of Technology, Stanford's Peace and Innovation Lab, Georgia Institute of Technology, Stanford University, Boeing, Aurora Flight Sciences, Zee Aero, Airbus, Terrafugia, EmbraerX, XTI Aircraft Company, Joby Aviation, Uber, Global Aerospace, HR&A Advisors, Starburst Aerospace, and GE Ventures. Booz Allen team engaged SAG members throughout the study through informational interviews and a day-long workshop that took place in Washington, DC.

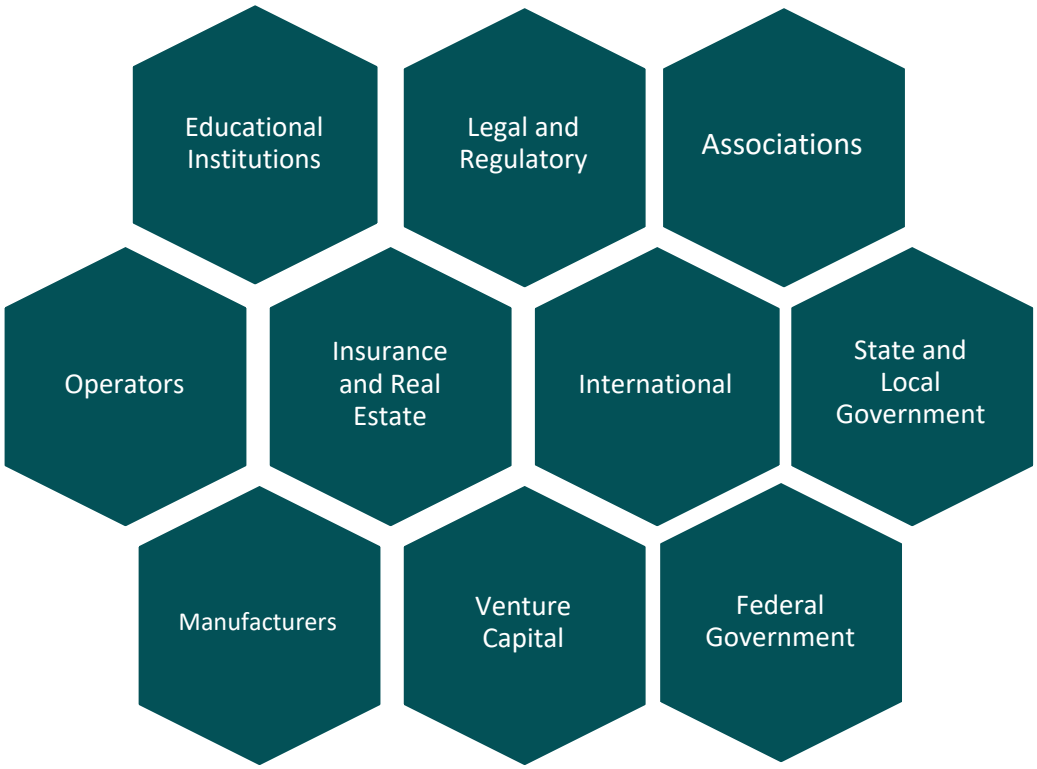

Figure 3: SAG Member institution type

5.0 FOCUS MARKETS

Depending on vehicle technology, operations, economics and market size, Urban air transportation could take many forms. As described in Table 1, the team identified 36 potential UAM markets across 16 market categories.

Table 1: Potential UAM Markets

Market Category	Potential UAM Market	Definition
Air Commute	Airport Shuttle	Comprises establishments primarily engaged in transporting passengers to, from, or between airports over fixed routes
	Air Taxi	Providing point-to-point passenger transportation and are not operated on regular schedules or routes
	Train	Providing concentrated point-to-point travel along network infrastructure (like trains/subway)
	Bus	Replacing public transportation routes & charter lines such as Greyhound & BestBus
First Response (Public Services)	Air Ambulance	Travel to/from the hospital for emergencies and potentially hospital visits
	Police – Local, State, and Federal	Law enforcement individuals enabled by air support for daily tasks and events management
	Firefighter – Private, Municipal, and Federal	Quick response firefighting enabled by air mobility travel
	Natural Disaster and Armed Conflict Response – Local, State, and Federal	Air support for aiding humanitarian workers and for evacuation efforts, in addition to the police, ambulance, and firefighting professionals during a natural disaster and armed conflicts
Corporations	Company Shuttle	Shuttle to and from a company headquarters to other offices or employee services
	Office-to-Office Travel	Travel to and from specific offices in adjacent skyscrapers
	Inter-office / Client Delivery	Deliver legal/business documents, replacing inter-office mail and traditional courier services
Events	Major Events	Pick up and drop off for events with a capacity greater than 25K people
	Minor Events	Pick up and drop off for events greater than 100 people but less than 25K
Entertainment and Media	Amusement Parks / Extreme Sporting	Thrill ride (i.e., trackless roller coaster), aerial acrobatics platform, bungee jump/parachuting platform
	Photography	Aerial Photography
	Film/TV/Radio Stations	Filming, Traffic and News Reporting
	Tourism	Aerial Sightseeing Tours

Logistics and Goods Delivery	Aerial Delivery	UAM aircraft and drones to deliver mails, food, humanitarian aid, shopping items etc.
	Aerial Warehousing	Using aerial craft to facilitate goods delivery, warehousing, and logistics management
Real Estate and Construction	Aerial Showcasing, Inspections, and Survey –Property Inspection and Real Estate Showcasing	Building, house, or land inspection and survey by certified inspectors, surveyors or private owners for repair and maintenance Realtors showing prospective client neighborhoods, parcels, and even attending an open house or broker's open house
Security	Aerial Security	Video footage or pictures from the sky to identify security weaknesses in various events
Rentals	Car Rentals – Corporation and Franchise	Replacing daily car rentals
Asset/Building Maintenance	Building Maintenance	Servicing building exteriors, such as painting and window washing, to replace current access methods such as pulley platforms that occasionally result in injury/death
	Utilities Asset Maintenance	Servicing electrical wires, smart poles, and certain meter types, to replace current access practices such as pole climbing that occasionally result in injury/death
Healthcare Providers	Remote Visits	Pickup and drop-off of provider or patient for patients living in remote areas
	Medical Equipment Delivery	Delivery of urgently needed medical items; for expensive diagnostic tools, establish sharing program where delivery to next user is scheduled immediately after use at the first location
Scientific Research	Aerospace Travel/Colony Pilot Studies	Study effects of long-term space travel, life above terrain, new types of aviation technology/process, etc. using potentially less expensive and safer-context UAMs
	Other Applications	Conducting scientific research using other applications elucidated in this list (deforestation, migration patterns, etc.)
Urban Planning	Small Houses/ Emergency Shelters	Modifications to UAMs to create permanently air-parked shelters in crowded environments, crime-prone locations, attached to owner home, etc.
Security	Storage	Modifications to UAMs to create temporary storage space where building permanent addition may not be feasible
Public Services (Non-First Response)	Snowplow & Salt Trucks	Replacing winter snowplow and salt trucks
	Trash Collection	Replacement of trash trucks, hazardous waste disposal, etc.
	School Buses	Replacing public school buses

Agriculture	Flock Tending	Reaching remote flocks for herding, medical care
	Harvesting	Reaching less-accessible farmland for planting, harvesting, potable water
	Landscaping	Replacing ladders and tree-climbing assists with UAMs for tree limb removal

The focus market types were selected using a market calibration criterion as described in Figure 4 to reflect and allow for the analysis of a diverse set of barriers, including operational models and efficiency, market size, dependency with other modes of transportation. The team evaluated each market type based on value and size of legacy market and economic, technological and operational challenges. As described in Table 2, the three markets selected included (1) Airport Shuttle, (2) Air Taxi, and (3) Air Ambulance.

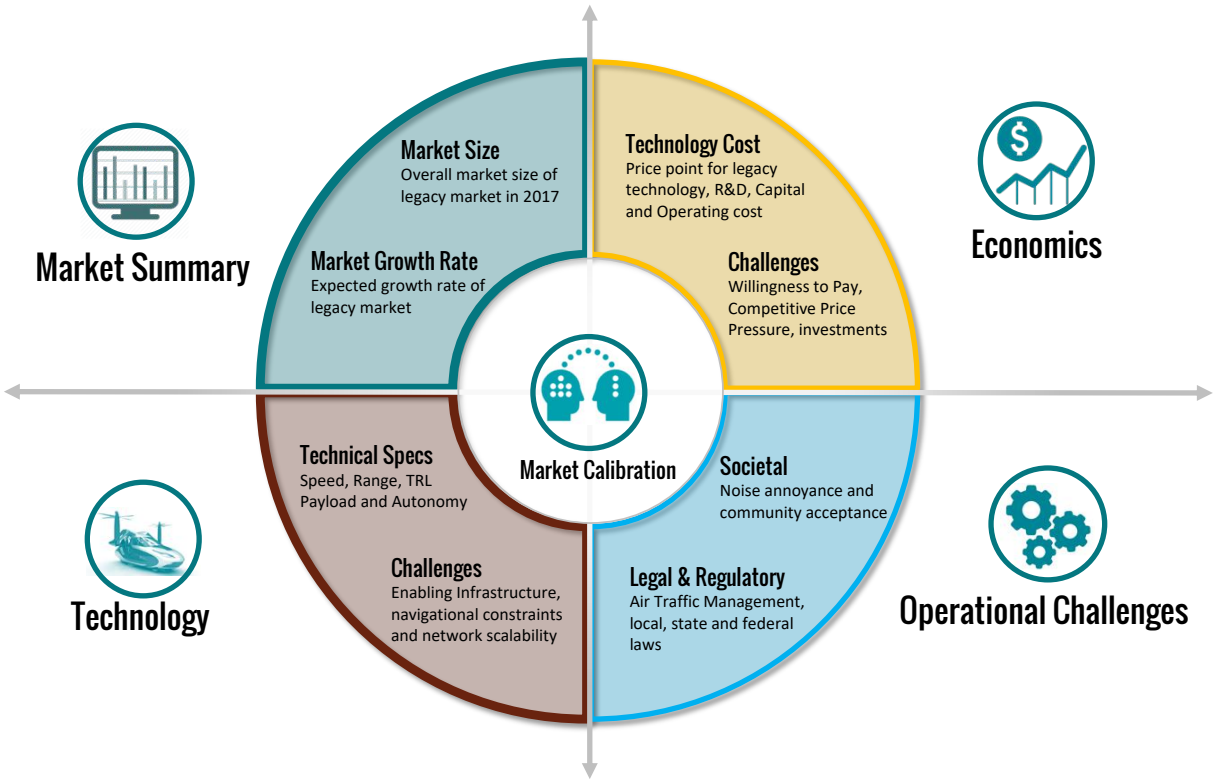

Figure 4: Market selection criteria

Table 2: Focus Markets

Market	Definition	Selection Logic
Airport Shuttle	Early market that comprises establishments primarily engaged in transporting passengers to, from, or between airports over fixed routes. This market could originate as a premium service to high value passengers of airlines	This market was selected as an early adopter due to: • **Operational Efficiency:** Concentrating the demand at one end of the flight could reduce complexity of supply/demand matching and increase the operational efficiency.

	and mature to a mainstream transportation option for travelers in the future. This market could eventually grow into an aggregate Air Taxi market.	• **Infrastructure:** Foundational infrastructure for takeoff/landing areas exists on at least one side of the flight. • **Enablers:** Some large airlines may be looking for ways to differentiate premium services to high value customers by creating efficient travel connections to and from the airport.
Air Taxi	Scaled UAM market that will provide point-to-point passenger transportation and are not operated on regular schedules or routes. Air taxis can operate throughout urban areas and provide a variety of transportations services.	This market was selected due to: • **Large Market:** A scaled UAM market that could highlight barriers related to scale of people served; this market is analogous to similar ground services, but would provide an added resiliency to transportation networks and convenience of time saved. *Note: This market could be a natural extension of the Airport Shuttle market as the density of demand for UAM increases with increasing fleet size and service area coverage.*
Air Ambulance	Complex market that includes travel to/from the hospital for emergencies and potentially hospital visits. The Air Ambulance market is concentrated; however, the services offer a high value. This market is driven by demographic trends, healthcare legislations, and changes in insurance policies.	This market was selected due to: • **Market complexity**: This market highlighted technology barriers in terms of technical capabilities needed on board the aircraft, in addition to other legal and regulatory barriers.

6.0 FOCUS URBAN AREAS

For the purpose of this study, an Urban Area includes a city center, suburban area and edge cities. For example, in the Washington, D.C. urban area, downtown D.C. is defined as city center while Virginia as suburban and Tyson's corner as an edge city. Urban areas are defined in Figure 5.

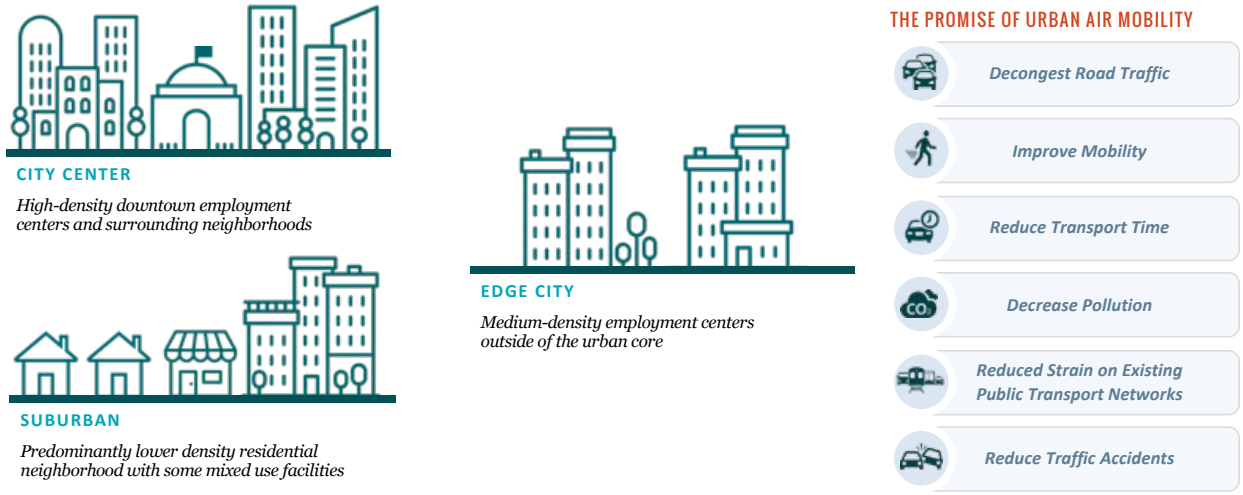

Figure 5: Definition of Urban Areas and promise of Urban Air Mobility

According to the United States Census Bureau (2010), there are 486 urbanized areas (UAs) and 3,087 urban clusters (UCs) in the United States. Urbanized areas comprise of approximately 88% of the urban population in the United States. Selected urban areas are representative of the U.S. and captured a wide set of operational and market barriers.

Figure 6 shows the detailed process that was followed to select urban areas. Selected urban areas had large population and high population density, high surface traffic congestion, favorable/unfavorable weather conditions and legal/regulatory environment, potentially large markets, available infrastructure and competition from existing modes of transportation. Details on the scoping criteria is as follows:

Population Filter: The team filtered out small urban areas to focus on a representative set of large urban areas that can highlight the most significant barriers. Two factors used to identify large urban areas were:

- **Population:** Applied filter of urban area population greater than one million to select large urban areas.
- **Population Density:** Applied filter of population density greater than 1000 people per square mile to select areas of high population density

Surface Traffic Congestion at each urban area was modeled with respect to the following indices:

- **Travel Time Index:** The ratio of the travel time during the peak period to the time required to make the same trip at free-flow speeds. For example, a value of 1.3 indicated that a 20-minute free-flow trip would take 26 minutes during the peak period.
- **Commuter Stress Index:** Similar to the Travel Time Index but based only on the peak direction of travel. This would be more like the traditional commuter experience of inbound in the morning and outbound in the evening.
- **Annual Congestion Cost**: Value of travel delay and extra fuel consumed in traffic congestion. It was measured in billions of dollars.

Higher annual congestion cost, travel time and commuter stress index reflected high traffic congestion and thus greater market opportunity for UAM.

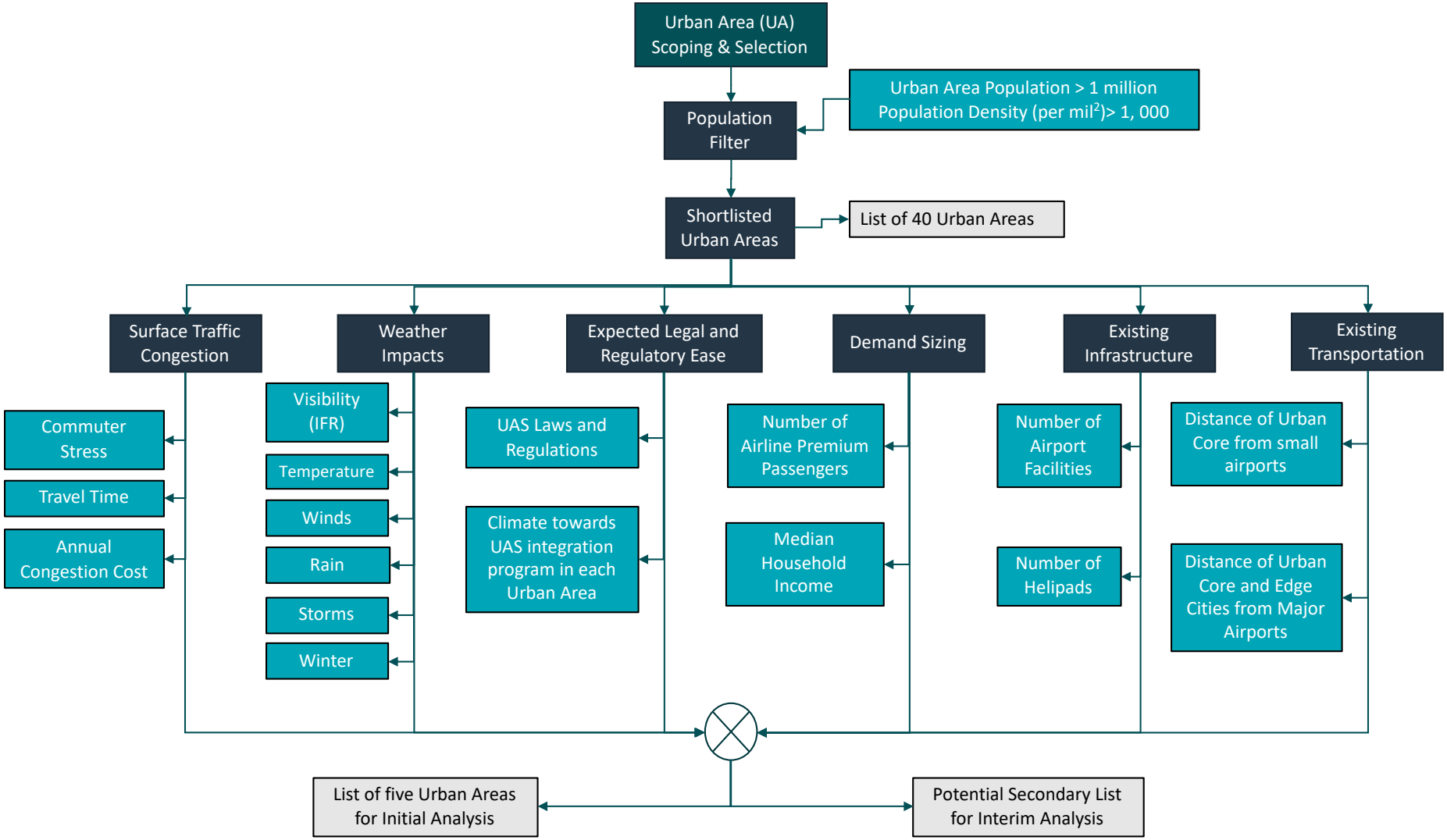

Figure 6: Urban Area Selection Process

Weather Impacts:

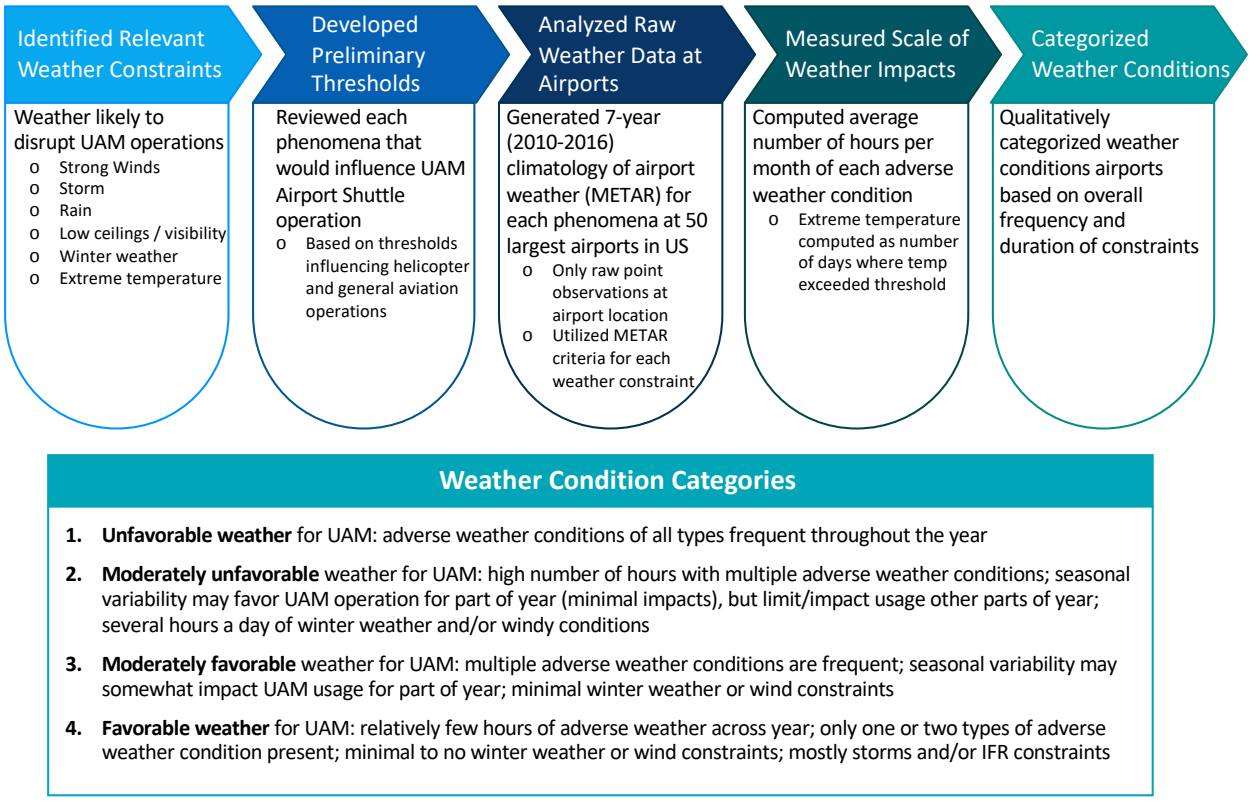

Figure 7: Weather Impacts

Expected Legal and Regulatory Ease: UAM use cases did not have historical laws and regulations to inform Urban Area Scoping. Therefore, our legal team classified urban areas based on:

- **State UAS Laws:** Reviewed state and local laws and restrictions on flight altitude and flight paths, operational bans, and any regulation of the navigable airspace
- **UAS Integration Program:** Reviewed each state's climate towards integrating Unmanned Aircraft System (UAS) in their airspace
- **GA related State laws**: Reviewed restrictions of flying private aircraft in each state

The Booz Allen team qualitatively categorized each of the top 40 urban area (obtained after population filter) airspace based on these laws as:

- **Favorable regulations for UAM***:* Phoenix, Miami, San Diego, Orlando
- **Moderately favorable regulations for UAM***:* San Francisco, Los Angeles, Houston, Dallas
- **Moderately unfavorable regulations for UAM***:* Salt Lake City, Kansas City, Providence, Columbus
- **Unfavorable regulations for UAM***:* New York, Washington DC, Boston, Denver

Demand Sizing: First order estimate of expected market size for each of the shortlisted urban areas was modeled in terms of number of premium airline passengers in an urban area. Existence of premium originating and terminating passengers represented first order highest willingness to pay for premium services. We calculated number of premium passengers for each urban area using:

- **Bureau of Transportation Statistics (BTS) DB1B[1]:** Retrieved 2010-2016 BTS DB1B Coupon Data by Fare Class
- **Fare Class Classification:** Business and First-Class passengers were classified as Premium passengers
- **Total annual average number of passengers for each airport**: Since BTS covers a 10% sample of airline tickets, total number of passengers were multiplied by 10. Average number of passengers were calculated across 2010-2016
- **Market Size aggregation for an urban area**: Number of premium passengers were aggregated for all the major commercial airports in an urban area

Existing Infrastructure: Early Urban Air Mobility markets might rely on existing infrastructure like heliports, airports and other landing sites for near term. We used Federal Aviation Administration's Aviation Environment Design Tool (AEDT)[2] database. For urban area scoping, the team based its evaluation of existing infrastructure on:

- **Helipads:** All helipads active or non-active, public or private are considered part of existing infrastructure
- **Airports:** Major commercial airports, general aviation and small airfields provide landing sites at one side of the airport shuttle trip

Greater number of total helipad and airport facilities was found to be favorable for enabling Urban Air Mobility.

Existing Transportation: UAMs value proposition depends upon travel time savings. For example, Airport shuttle market will add value in the urban areas where distance is large between airports and urban core or edge cities. Therefore, the team evaluated urban areas based on:

- **Average distance between major commercial airports and urban core / edge cities:** Target population included airline passengers flying on scheduled routes between two cities
- **Average distance between small airports and urban core / edge cities:** Target population included business commuters using private jets or chartered service

Finally, to evaluate all the twelve metrics under six different categories, the team reorganized the data structure by using a normalization technique that was relative to minimum and maximum value of the metric. Higher percentage of a metric for an urban area meant higher expected market opportunity relative to other urban areas due to that metric. After applying our methodology, we selected five urban areas for initial analysis and five additional urban areas for interim analysis from a shortlisted pool of 40 Urban Areas. We selected urban areas that were representative of the US and illuminated wide set of barriers for the Airport Shuttle and Air Taxi market operated with human pilots or autonomously.

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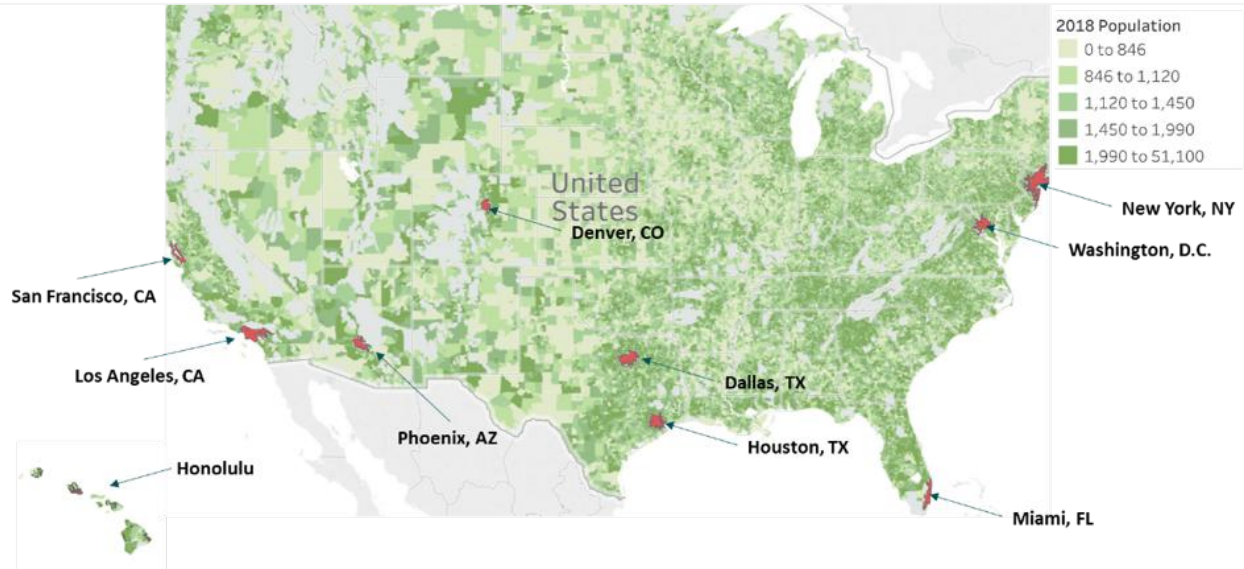
[1] "The Airline Origin and Destination Survey (DB1B) is a 10% sample of airline tickets from reporting carriers collected by the Office of Airline Information of the Bureau of Transportation Statistics. Data includes origin, destination and other itinerary details of passengers transported. This database is used to determine air traffic patterns, air carrier market shares and passenger flows." It is available at https://www.transtats.bts.gov/DatabaseInfo.asp?DB_ID=125

[2] Federal Aviation Administration. "AEDT is a software system that models aircraft performance in space and time to estimate fuel consumption, emissions, noise, and air quality consequences. AEDT is a comprehensive tool that provides information to FAA stakeholders on each of these specific environmental impacts." Available at https://aedt.faa.gov/

Figure 8 illustrates and provides characteristics of the ten urban areas that were selected and retained for the remainder of the study towards the market size and barriers assessments.



New York--Newark, NY--NJ--CT	Multi airport model, largest market, tough local and state regulations, unfavorable weather conditions, high traffic congestion
Washington, DC--VA—MD	Most regulated urban area, unfavorable weather conditions
Miami, FL	Luxury market, favorable weather conditions, medium to high traffic congestion, favorable regulatory environment
Dallas--Fort Worth--Arlington, TX	Large market, good weather conditions, high willingness to pay, large number of edge cities and good available infrastructure
Houston, TX	Two airport model, large market, favorable weather conditions, good existing infrastructure
Denver--Aurora, CO	One airport model, luxury market, changing weather conditions, difficult airport accessibility, especially if flying into the mountains
Phoenix--Mesa, AZ	Favorable regulatory and weather conditions, early adopter
San Francisco--Oakland--San Jose, CA	Multi airport model, high willingness to pay, large market, high traffic congestion, technology forward
Los Angeles--Long Beach--Anaheim-- Riverside--San Bernardino, CA	Multi airport model, high willingness to pay, large market, high traffic congestion, good available infrastructure
Urban Honolulu– Kailua, Kaneohe--Kahului, HI	Luxury market, good weather conditions, island to island travel

Figure 8: Focus Urban Areas

7.0 LEGAL AND REGULATORY ASSESSMENT

Technology very quickly outpaces regulation. With Urban Air Mobility, as with other disruptive technologies, federal, State, and local-level governments must find a "sweet spot" where innovation is not stifled, and the public is reasonably protected. Urban Air Mobility operations raise novel and valid concerns, namely in terms of safety and privacy, and some legal barriers exist which can discourage the use of such technology. However, these legal barriers are accompanied by collaborative opportunities such as the UAS Integration Pilot Program, FAA Rulemaking Committees, the UAM Grand Challenge, and others, which allow for the alignment of technology and regulation, creating new enabling rules that allow for more complex operations.

7.1 Methodology

This assessment identified the legal and regulatory requirements (existing and anticipated) that must be met for the selected three focus UAM markets. It also captured variations in requirements observed at the State and local level, international developments, certification issues, and existing opportunities to address legal barriers and gaps.

Our team examined the law and regulatory conditions needed for the UAM markets to perform in selected urban areas under the following operations: (1) onboard pilot, (2) remotely operated, and (3) partial or fully automated piloting system. We analyzed the rules associated with the three types of UAM operations, including: (1) federal Acts, (2) federal regulations, (3) state laws and local ordinances for each of the ten urban markets, and (4) international and foreign law. It is important to note that the analysis draws a comparison of the legal and regulatory challenges for UAM with those of the Unmanned Aircraft Systems (UAS), especially as to how it relates to remotely piloted and autonomous vehicles.

As a summary, our analysis shows that the remotely piloted and autonomous Air Taxi, Ambulance, and Airport Shuttle UAM markets share common regulatory barriers. However, state and local laws range from disallowing drones to protecting UAS operations, which might be problematic considering the "patchwork" of laws it can create. Similarly, other nations integrate UAS into their airspace in varying degrees. Moreover, there will be challenges in determining which of the existing FAA certification standards apply to the types of vehicles being considered for the Air Taxi or Air Ambulance UAMs, and/or how existing certification standards can be met or should be amended. Air Ambulances will require further evaluation due to the requirements of an operator's air ambulance procedures and sections of their General Operations Manual (GOM) specific to air ambulance. Lastly, gaps in current certifications indicate that new standards will need to be developed, especially in areas related to system redundancy and failure management.

7.2 Legal and Regulatory Barriers

Critical legal and regulatory challenges must be addressed to bring UAM transportation to the market. Air Taxi, Ambulance, and Airport Shuttle UAM Markets share common regulatory barriers. This analysis draws a comparison of legal and regulatory challenges for enabling UAM with Unmanned Aircraft Systems (UAS). Many of the UAM areas are being addressed to some extent with the emergence of UAS operations, and UAS research has helped reduce gaps towards enabling UAM. The laws for operations using an onboard pilot are clearer as they already exist under 14 Code of Federal Regulations (CFR) Parts 21, 23, 25, 27, 36, 61, 91, and 119. However, remotely piloted and autonomous UAM operations require the following aviation regulations (either modification of existing regulations, or new regulations):

- Regulations for beyond visual line of sight (currently only with lengthy waiver process to 14 CFR Part 107.31)
- Regulations for operations over people, streets, etc. (currently only with lengthy waiver process to 14 CFR 107.39)
- Regulations for when air cargo is being carried commercially and across state lines (this is addressed in Section 348 of the FAA Reauthorization Act of 2018[3] whereby Congress tasks the FAA within the year with making regulations for the carriage of property for compensation or hire)

[3] Federal Aviation Administration Reauthorization Act of 2018, §348.

- Regulations for when a passenger or patient is being transported in a UAM either within visual line of sight or beyond (airworthiness potentially addressed in 14 CFR Part 23)
- Regulations for flight in instrument conditions (not addressed in the FAA Reauthorization Act of 2018)
- Regulations for airworthiness certification of remotely piloted and autonomous aircraft
- Training and knowledge requirements for pilots and operators (FAA Reauthorization Act of 2018 Section 349 whereby Congress tasks the FAA with creating an aeronautical knowledge test for certain recreational UAS operators)

Additionally, a legal framework for addressing privacy concerns should be developed outside of the aviation regulatory framework. The recently passed FAA Reauthorization Act of 2018 makes a step in that direction by mandating the Department of Transportation and National Telecommunications and Information Administration (NTIA) of the Department of Commerce "to identify any potential reduction of privacy specifically caused by the integration of unmanned aircraft systems into the national airspace system."[4]

7.2.1 Federal versus State "Tug of War"

A dynamic legal environment exists with many unresolved challenges, especially establishing where federal, State, and local authorities take lead. Where the Federal government occupies a field, federal laws preempt state laws and local ordinances. The 1958 Federal Aviation Act delegated the safe and efficient use of the airspace to the FAA requiring it to create and enforce federal regulations (under Title 14 of the CFR). As such, the FAA has exclusive authority over the national airspace. With respect to UAS, the FAA issued its first rule governing commercial drone operations in 2016.

On the other hand, the 10th Amendment to the Constitution gives States/local government the rights and powers "not delegated to the United States." States are granted the power to establish and enforce laws protecting the welfare, safety, and health of the public (police powers). This authority can prevent trespass, nuisance, invasion of privacy, and a slew of other issues that UAS can cause. However, although state and local governments have passed laws of their own, a drone cannot fly freely across city and state lines if inconsistent laws interfere with its path.

A "tug of war" exists between federal preemption and state/local police power as each government entity is vying for the power to regulate. Not many courts across the country have settled this power struggle. In aviation tort law there is some clarity, but in UAS operations there is only one case of first impression: Singer vs. City of Newton, MA (Sept. 2017).[5]

In December 2016, the City of Newton, MA passed a local ordinance banning UAS below 400 feet and requiring operators to register their UAS and receive permission from public and private residence owners in order to fly their UAS over their homes. This local ordinance was drafted "for the principal purpose of protecting the privacy interests of Newton's residents," according to a court document.

In September 2017, a federal judge ruled against this local ordinance, allowing operators to use UAS that fly below 400 feet and without permission of city residence owners, in accordance with 14 CFR 107 regulations. The ruling in this case was the first of its kind, setting a legal precedent that says when it comes to certain UAS operations disputed in this case, federal law preempts local regulations. A city cannot regulate flight operations, and it may not effectively ban drone flights against the express congressional intent to encourage drone use.[6] Even though the ordinance intended to protect the city citizens' privacy, portions of it extended into the FAA's operational safety and licensing authority and was struck down.

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[4] *Id.* §335.

[5] Singer v. City of Newton, No. CV 17-10071, 2017 WL 4176477 (D. Mass. Sept. 21, 2017).

[6] 49 U.S.C. § 40101.

7.2.2 UAS Integration Pilot Program (UAS IPP)

In what appears to be a way to settle the above mentioned "tug of war", and more importantly to prevent the painfully slow lawmaking process from stifling the growth and development of the emergent UAS industry, the UAS IPP encourages the FAA to work closely with State, local, and Tribal governments and private sector entities such as UAS operators or manufacturers, to accelerate safe UAS integration. This program will help FAA craft new enabling rules that allow more complex operations governing the carriage of passengers and cargo, flights over people, and flights beyond visual line of sight. This process was started in November 2017 as is ongoing as of this writing.

7.3 State and Local Regulatory Arena

As stated earlier, the analysis on UAM draws a comparison to the UAS legal and regulatory achievements as many of the UAM areas are being addressed to some extent with the emergence of UAS operations. Similarly, UAS research has helped reduce the gap towards enabling UAM. As stated above in Section 7.2.1, the FAA has exclusive authority over the national airspace, and no State or local UAS registration law may relieve a drone owner or operator from complying with the federal drone regulations. However, local concerns such as those pertaining to the welfare, safety, and health of the public (police powers), such as land use, law enforcement, zoning, privacy, and trespass issues are usually not subject to federal regulations.

Though most of the attention paid to drones has focused on the FAA and its regulatory authority, much of the impact is at the ground level. This will be the case with UAM as well. As such, States and local governments have been passing drone-related laws since 2013, citing the need to protect the health and safety, including privacy, of residents. These state and local drone laws can be seen as the precursor to UAM local laws, especially when it pertains to remotely-piloted and autonomous vehicles.

A review of the State and local laws and regulations is important to showcase the evolution of legislation which UAM could benefit from and face. UAS have many applications including law enforcement, search and rescue, border patrol, disaster response, land surveillance, wildlife tracking, and photography. Due to the wide variety of benefits, States and local governments since 2013 have been pushing for regulations, ordinances, and resolutions which consider the benefits and potential economic benefit of using UAS, while weighing privacy concerns. It is important to note that States do not regulate or govern manned aviation. State policy does guide where, when, and how much air commerce it attracts. Additionally, airports and heliports and the cities who own them enter into agreements for service at the local level, not at the Federal level.

Below is an overview of regulations enacted by each of the selected ten (10) urban areas. State and local laws range from banning drones to protecting UAS operations. These regulations apply to remotely piloted or autonomous operations, which is seen as a precursor to similarly operated UAM vehicles.

Arizona:

Arizona has a law favoring first responders.

- **SB 1449**: Prohibits certain operation of UAS, including operation in violation of FAA regulations and operation that interferes with first responders. The law prohibits operating near, or using UAS to take images of, a critical facility. It also preempts any locality from regulating UAS.[7]

[7] Arizona, SB1449, https://www.azleg.gov/legtext/52leg/2r/bills/sb1449p.pdf (last visited Nov. 14, 2018).

California:

California has laws favoring first responders.

- **SB 807** was chaptered (entered into law): Limits the exposure to civil liability of an emergency responder for damage to a UAS if the damage was caused while the emergency responder was performing specific emergency services and the UAS was interfering.[8]
- **AB 1680**: UAS going to the scene of an emergency or stopping at the scene of an emergency, for the purpose of viewing the scene or the activities is a misdemeanor.[9]

Colorado:

Colorado has no laws regarding the use of UAS.

- **HB1070**: Requires the center of excellence within the department of public safety to perform a study. The study must identify ways to integrate UAS within local and state government functions relating to firefighting, search and rescue, accident reconstruction, crime scene documentation, emergency management, and emergencies involving significant property loss, injury or death. The study must also consider privacy concerns, costs, and timeliness of deployment for each of these uses. The legislation also creates a pilot program, requiring the deployment of at least one team of UAS operators to a region of the state that has been designated as a fire hazard where they will be trained on the use of UAS for the above specific functions.[10]

Florida

- **HB 1027**: Preempts local governments from regulating the operation of unmanned aircraft systems but does allow them to enact or enforce local ordinances relating to illegal acts arising from the use of unmanned aircraft systems if the ordinances are not specifically related to the use of a drone for the commission of the illegal acts.[11]
- **SB 92**: Law enforcement may use a drone if they obtain a warrant, there is a terrorist threat, or swift action is needed to prevent loss of life or to search for a missing person. The law also enables someone harmed by an inappropriate use of drones to pursue civil remedies.[12]
- **SB 766**: Prohibits a person, a state agency, or a political subdivision from using a drone to capture an image of privately owned real property or of the owner, tenant, occupant, invitee, or licensee of such property with the intent to conduct surveillance without his or her written consent if a reasonable expectation of privacy exists.[13]
- **Miami Ordinance 37-12**: Regulates the use of UAS within a half-mile radius around stadiums and sport facilities when these devices are in use, and over other large venue special events in public parks, public facilities, streets, plazas, open spaces and the like that will attract large groups of people.[14]

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[8] California, SB 807, https://legiscan.com/CA/bill/SB807/2015 (last visited Nov. 14, 2018).

[9] California, AB1680, http://www.leginfo.ca.gov/pub/15-16/bill/asm/ab_1651-1700/ab_1680_bill_20160929_chaptered.pdf (last visited Nov. 14, 2018).

[10] Colorado, HB1070, https://openstates.org/co/bills/2017A/HB17-1070/ (last visited Nov. 14, 2018).

[11] Florida, HB 1027, https://www.flsenate.gov/Session/Bill/2017/1027 (last visited Nov. 14, 2018).

[12] Florida, SB 92, https://www.flsenate.gov/Session/Bill/2013/0092 (last visited Nov. 14, 2018).

[13] Florida, SB 766, https://www.flsenate.gov/Session/Bill/2015/0766 (last visited Nov. 14, 2018).

[14] Miami Ordinance 37-12, https://library.municode.com/fl/miami/codes/code_of_ordinances?nodeId=PTIITHCO_CH37OFIS_S37-12PUSAUNAISYCOKNDR (last visited Nov. 14, 2018).

Hawaii

Has a law that prohibits UAS except for law enforcement.

- **SB 2608:** Prohibits the use of unmanned aircraft, except by law enforcement agencies, to conduct surveillance and establishes certain conditions for law enforcement agencies to use an unmanned aircraft to obtain information.[15]

New York, NY

Drones are more formally known as unmanned aerial vehicles (UAV) and are illegal to fly in New York City.

- **SB975:** Prohibits municipalities from regulating UAS. It allows a municipality that is also a water company to enact ordinances that regulate or prohibit the use or operation of UAS over the municipality's public water supply and land.[16]

Texas

- **SB840:** Telecommunications providers may use UAS to capture images. Only law enforcement may use UAS to captures images of real property that is within 25 miles of the U.S. border for border security purposes.[17]
- **HB 1424:** Prohibits UAS operation over correctional and detention facilities. It also prohibits operation over a sports venue except in certain instances.[18]
- **HB 1481:** Makes it a Class B misdemeanor to operate UAS over a critical infrastructure facility if the UAS is not more than 400 feet off the ground.[19]
- **HB1643:** Adds telecommunications services structures, animal feeding operations, and oil and gas facilities to the definition of critical infrastructure as it relates to UAS operation. Prohibits localities from regulating UAS except during special events and when the UAS is used by the locality.[20]
- **HR 3035:** Identifies 19 legitimate commercial purposes for UAS operations and prohibits UAS photography and filming of property or persons without prior consent.[21]

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[15] Hawaii, SB 2608, https://www.capitol.hawaii.gov/Archives/measure_indiv_Archives.aspx?billtype=SB&billnumber=2608&year=2014 (last visited Nov. 14, 2018).

[16] New York, SB975, https://openstates.org/ct/bills/2017/SB975/ (last visited Nov. 14, 2018).

[17] Texas, SB840, http://www.capitol.state.tx.us/tlodocs/85R/billtext/pdf/SB00840F.pdf#navpanes=0 (last visited Nov. 14, 2018).

[18] Texas, HB1424, http://www.capitol.state.tx.us/tlodocs/85R/billtext/pdf/HB01424F.pdf#navpanes=0 (last visited Nov. 14, 2018).

[19] Texas, HB1481, https://capitol.texas.gov/BillLookup/History.aspx?LegSess=84R&Bill=HB1481 (last visited Nov. 14, 2018).

[20] Texas, HB1643, http://www.capitol.state.tx.us/tlodocs/85R/billtext/pdf/HB01643F.pdf#navpanes=0 (last visited Nov. 14, 2018).

[21] Texas, HR 3035, http://www.statutes.legis.state.tx.us/Docs/GV/htm/GV.423.htm (last visited Nov. 14, 2018).

Washington, D.C. Metropolitan Area

- Maryland:
  - **SB 370:** Specifies that only the state can enact laws to prohibit, restrict, or regulate the testing or operation of unmanned aircraft systems. This preempts county and municipal authority. The bill also requires a study on specified benefits.[22]
- Washington, D.C. is a no drone zone.
- Virginia:
  - **HB 412:** Provides that no locality may regulate the use of privately owned, unmanned aircraft systems within its boundaries.[23]
  - **HB 2350:** Makes it a Class 1 misdemeanor to use UAS to trespass upon the property of another for the purpose of secretly or furtively peeping, spying, or attempting to peep or spy into a dwelling or occupied building located on such property.[24]
  - **SB 1301:** Requires that a law enforcement agency obtain a warrant before using a drone for any purpose, except in limited circumstances.[25]

7.4 International Regulations

International harmonization of regulations may be important as countries consider similar operating concepts and UAM manufactures, operators, and service providers seek consistency in a potential worldwide market. The following depicts several organizations and Nation-States who have developed regulations in furtherance of UAS, with such UAS research and regulatory movement helping to reduce the gap towards enabling UAM activities.

7.4.1 European Aviation Safety Agency (EASA)

After a four-month consultation period on the Notice of Proposed Amendment (NPA) 2017-05[26], EASA published Opinion 01/2018[27], including a proposal for a new Regulation for UAS operations in 'open' and 'specific' category.

- 'Open' category is a category of UAS operation that, considering the risks involved, does not require a prior authorization by the competent authority nor a declaration by the UAS operator before the operation takes place;
- 'Specific' category is a category of UAS operation that, considering the risks involved, requires an authorization by the competent authority before the operation takes place, taking into account the

[22] Maryland, SB 370, https://legiscan.com/MD/bill/SB370/2015 (last visited Nov. 14, 2018).

[23] Virginia, HB 412, https://legiscan.com/VA/bill/HB412/2016 (last visited Nov. 14, 2018).

[24] Virginia, HB 2350, http://lis.virginia.gov/cgi-bin/legp604.exe?171+ful+HB2350ER+pdf (last visited Nov. 14, 2018).

[25] Virginia, SB 1301, http://lis.virginia.gov/cgi-bin/legp604.exe?ses=151&typ=bil&val=sb1301 (last visited Nov. 14, 2018).

[26] NPA 2017-05. *Introduction of a regulatory framework for the operation of drones — Unmanned aircraft system operations in the open and specific category*. https://www.easa.europa.eu/document-library/notices-of-proposed-amendment/npa-2017-05 (Accessed on Nov. 14, 2018).

[27] Opinion 01/2018. *Unmanned aircraft system (UAS) operations in the 'open' and 'specific' categories*. https://www.easa.europa.eu/document-library/opinions/opinion-012018. (Accessed on Nov. 14, 2018).

mitigation measures identified in an operational risk assessment, except for certain standard scenarios where a declaration by the operator is sufficient or when the operator holds a light UAS operator certificate (LUC) with the appropriate privileges; and

- 'Certified' category is a category of UA operation that, considering the risks involved, requires the certification of the UAS, a licensed remote pilot and an operator approved by the competent authority, in order to ensure an appropriate level of safety.

Additionally, on October 15, 2018, EASA proposed a rule to cover VTOL aircraft.[28] VTOL aircraft have unique features that "significantly differentiate them from traditional rotorcraft or aeroplanes and therefore necessitate this dedicated special condition." This proposed rule for the certification small-category VTOL applies to an aircraft with a passenger seating configuration of 5 or less and a maximum certified take-off mass of 2,000kg or less. This proposed rule could pose difficulties for VTOL weighing more than 2,000kg.

United Kingdom

Under the United Kingdom (UK) Civil Aviation Authority (CAA) rules[29], National Qualified Entities (NQEs) are established to assess the competence of people operating small unmanned aircraft as part of the CAA's process in granting operating permissions. Assessment by an NQE is necessary for those with no previous aviation training or qualifications. To achieve this, NQEs may offer a short educational course/program prior to the competency assessment aimed at bringing an individual's knowledge up to the required level (but please note that these are not CAA approved training courses). A typical NQE full-course involves:

- pre-entry/online study
- 1-3 days of classroom lessons and exercises
- a written theory test
- a flight assessment

Ireland

In Ireland, visual line of sight is quantified as 300m and UAS must stay 30m away from any person, vessel, vehicle or structure not under the direct control of the operator.[30]

New Zealand

The New Zealand Civil Aviation Authority defines a shielded operation as a flight where an aircraft remains within 100m of, and below the top of, a natural or man-made object such as a building, tower, or trees. [31] When flying as a shielded operation, an aircraft is allowed to fly at night, or within controlled airspace without ATC clearance, as other aircraft are unlikely to be flying so low and close to structures.

- Shielded operations within 4 km of aerodromes - If relying on the shielded operation provision to fly an unmanned aircraft within 4 km of an aerodrome, then in addition to remaining within 100m of, and below the height of the object providing the shield (e.g., a building or tree), there must also be a physical barrier like a building or stand of trees between the unmanned aircraft and the aerodrome. This barrier must be capable of stopping your aircraft in the event of a fly-away.

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28 Proposed Special Condition for VTO. https://www.easa.europa.eu/document-library/product-certification-consultations/proposed-special-condition-vtol. (Accessed on Nov. 14, 2018).

29 Guidance on Using Small Drones for Commercial Work. https://www.caa.co.uk/Commercial-industry/Aircraft/Unmanned-aircraft/Small-drones/Guidance-on-using-small-drones-for-commercial-work/. (Accessed on Nov. 14, 2018).

30 Drones. https://www.iaa.ie/general-aviation/drones. (Accessed on Nov. 14, 2018).

31 Intro to Part 101. https://www.caa.govt.nz/unmanned-aircraft/intro-to-part-101/#Shielded_Operations. (Accessed on Nov. 14, 2018).

Canada

Under Canadian law,[32] if the drone weighs over 250g and under 35kg and flying for fun, it must be flown:

- below 90 m above the ground
- at least 30 m away from vehicles, vessels and the public (if drone weighs over 250 g and up to 1 kg)
- at least 76 m away from vehicles, vessels and the public (if drone weighs over 1 kg and up to 35 kg)
- at least 5.6 km away from aerodromes (any airport, seaplane base or area where aircraft take off and land)
- at least 1.9 km away from heliports or aerodromes used by helicopters only
- outside of controlled or restricted airspace
- at least 9 km away from a natural hazard or disaster area
- away from areas where its use could interfere with police or first responders
- during the day and not in clouds
- within sight at all times
- within 500 m of pilot
- only if clearly marked with pilot's name, address and telephone number

United Arab Emirates

Key authorities in the United Arab Emirates include General Civil Aviation Authority (GCAA), Dubai Civil Aviation Authority (DCAA), and Roads and Transport Authority (RTA). The UAE contracted Volocopter for a 5-minute public test flight and announced plans for a 5-year path to UAM certification. The rules for UAS include (1) Registration, (2) Tracking and ID (Exponent Skytrax), (3) Insurance requirements, (4) Zones: 5 km from aerodromes, <400 ft, (5) No video or image capturing, (6) No BVLOS, (7) Certification, (8) Operator exam for commercial operations, and (9) COA for each commercial flight.

Germany

The Volocopter VC200 was granted provisional certification from German Ultralight Flight Association as an ultralight aircraft.

As the above listing of organizations and countries demonstrates, international harmonization of regulations is important to ensure consistency across the globe and to avoid a patchwork of laws and regulations. The next section will discuss standards and regulations for certification, and some efforts the International Civil Aviation Organization (ICAO), among other organizations, are undergoing to harmonize the patchwork of rules.

7.5 Airworthiness Certification Standards and Regulations

Airspace authorities use certification to manage the safety of aircraft, operators, and operations. All of these aspects of certification are important to UAM, and UAM will face challenges in each of these areas[33]. This analysis focuses on airworthiness certification, which addresses safety risks by setting requirements for

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32 Flying your Drone Safely and Legally. http://www.tc.gc.ca/en/services/aviation/drone-safety/flying-drone-safely-legally.html. (Accessed on Nov. 14, 2018).

33 Lascara, Brock, et. al. (April 2018). *Urban Air Mobility Landscape Report: Initial Examination of a New Air Transportation System*. https://www.mitre.org/sites/default/files/publications/pr-18-0154-4-urban-air-mobility-landscape-report_0.pdf.

aircraft design, manufacturing, performance, failure response, and maintenance. This applies to safety critical features, such as aircraft structure, engines, propellers, software, and electronics. Regulatory agencies develop requirements for airworthiness. Applicants must meet these requirements through "means of compliance", which may be based on regulatory guidance. In some cases, the certification authority will accept industry consensus standards developed by American Society for Testing and Materials (ASTM), Society of Automotive Engineers (SAE), Radio Technical Commission for Aeronautics (RTCA), and others as means of compliance.

Aircraft certification can act as a barrier for promoting rapid integration of emerging technologies for UAM. UAM aircraft challenge the existing certification process due to novel features and combinations of features, such as distributed electric propulsion / tilt-wing propulsion, VTOL, autonomy software, optionally piloted, energy storage, and ratio of aircraft to pilots being below 1. Certification can delay deployment of the technologies as they go through certification process that may take several years and can increase costs of deployments if the burden of compliance is high. Certification can also be an enabler as it provides passengers comfort that the standard for safety is sufficiently high. Our research identified trust in the technology as a critical societal barrier (see next chapter for more on societal barriers).

Questions considered in this analysis:

- How are new aircraft certified?
- What is the preferred path to certification for UAM aircraft (e.g., Part 23, 27, 21.17(b))?
- What are the gaps in requirements and means of compliance (e.g., RTCA DO-178C, ASTM F39)?
- What is being done to address these gaps?

7.5.1 Airworthiness Certification Approaches

Certification is a risk-based process. There is no such thing as zero risk aircraft operation. The certification framework is driven by questions about how society views the operations, such as: "What is society's risk tolerance for certain applications?", and "How strong is the desire for a low-cost solution?". For example, Part 107 for UAS includes no airworthiness certification for the aircraft. The aircraft and operation are deemed low risk, and there is a strong desire for low cost solutions. As the vehicle size increases, so does the risk and the need for more rigor. As the operation increases in risk, for example by carrying passengers that expect a certain level of safety, the level or rigor is further increased.

Aircraft are organized by category and class, which determines the risk regime that they reside in. The FAA and the North Atlantic Treaty Organization (NATO) certification categories are shown in Figure 9 and Figure 10. Certification requirements differ by class, and influence design of aircraft and heliports. For example, the following are requirements after critical loss of thrust:

- Transport category, airplane class: Certified to <u>2.4 – 3 percent climb gradient</u>
- Transport category A, rotorcraft class: Certified to <u>100 ft/min climb rate</u>
- Normal category, rotorcraft class: <u>no min climb rate</u>

NATO's risk calculation is based on a Military standard handbook for a casualty model based on current reliability data compared to the planned test flight route and population densities in areas along the planned flight route. Additional requirements are imposed on operations where less risk is accepted. Higher certification rigor means more cost and more time. Certification for Light Sport Aircraft can be in the hundreds of thousands of dollars, where Part 23 commercial aircraft can be in the tens to hundreds of millions of dollars. This tradeoff between risk tolerance and cost will drive the UAM certification approaches.

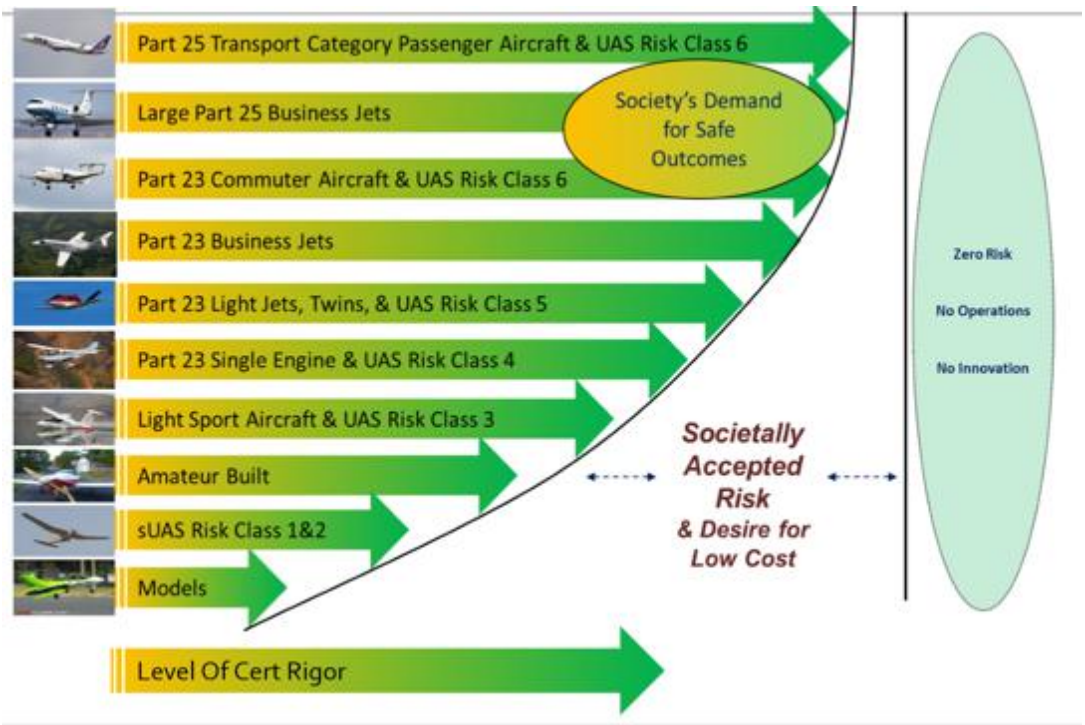

Figure 9: Trade-off between risk tolerance and level of certification rigor with FAA certification categories[34]

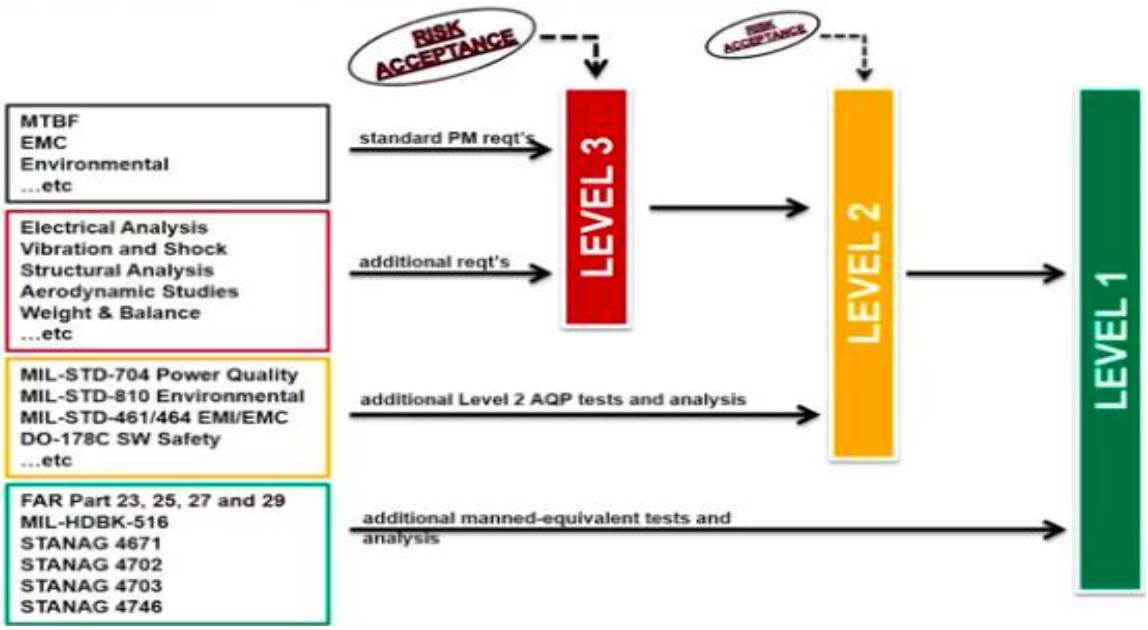

Figure 10: NATO STANAG level of certification rigor increases with lower risk acceptance[35]

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34 Gunnarson, Tom, (Jan. 2018). *Aircraft Type Certification Considerations*. AHS TVF Workshop. https://vtol.org/files/dmfile/13-TVF5-2018-Gunnarson-ASTM-Jan191.pdf.

35 Webber, David of FAA (May 2018, Time 38:17). *Flight Qualification and Certification of Advanced VTOL Aircraft*. Vertical Flight Society 74th Annual Forum. https://www.youtube.com/watch?v=JJf4u4MTiFs&feature=youtu.be.

7.5.2 International UAM Certification Landscape

Figure 11 summarizes international players and interactions for certification by capturing international activities, policies, standards, and working groups. This section describes more considerations of the potential paths to UAM certification, such as active governing bodies by domain.

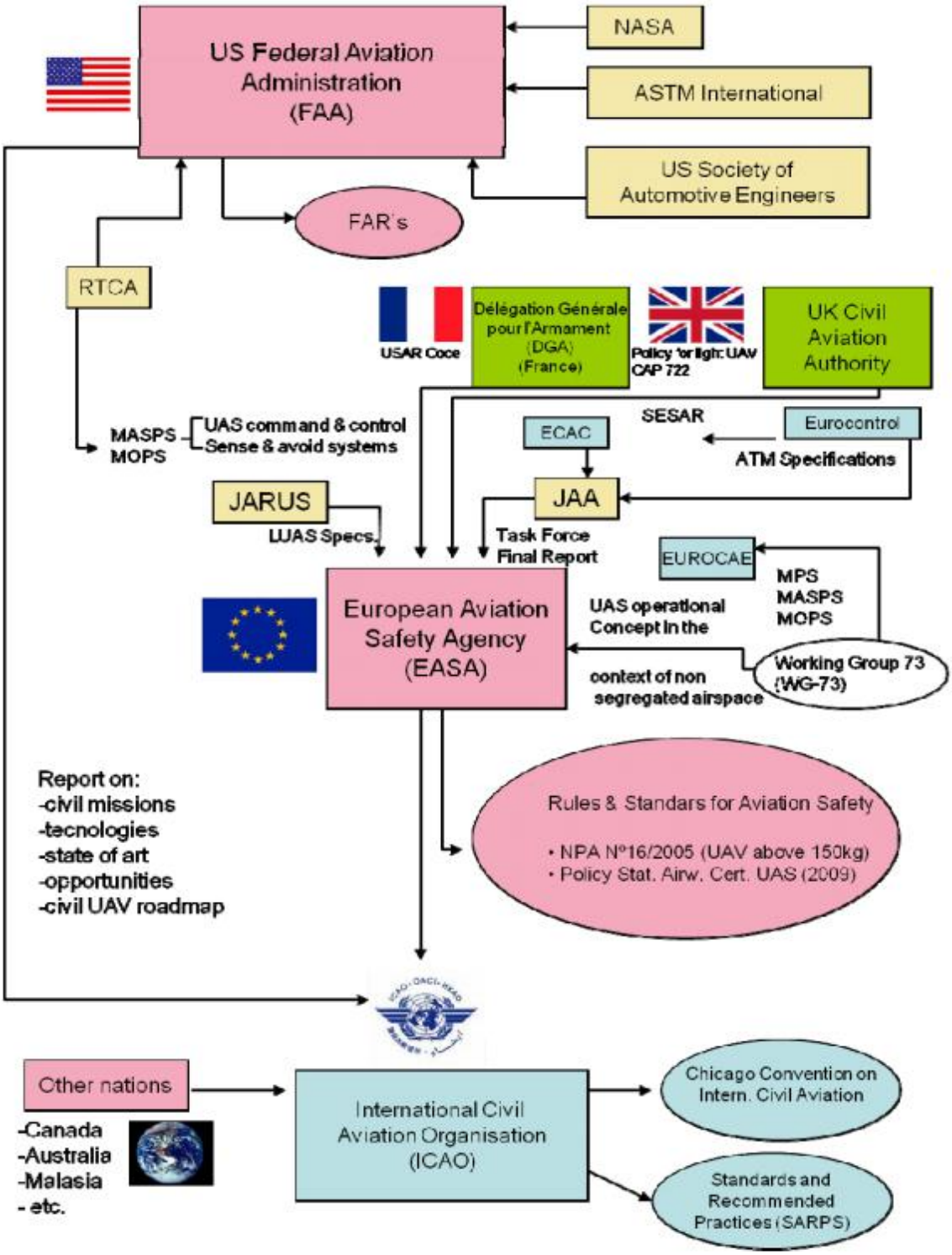


Figure 11: International UAS regulatory field (Cuerno-Rejado, 2010)

FAA certification is supported by activities and standards at NASA, SAE, and ASTM. ICAO is supported by bodies such as the Joint Authorities for Rulemaking on Unmanned Systems (JARUS), Joint Aviation Authorities (JAA), Single European Sky ATM Research (SESAR), as well as accepting guidance from other nations, including FAA and EASA. This is a quickly evolving ecosystem, and some recent developments are not reflected in this figure. For example, ICAO has established the Remotely Piloted Aircraft Systems Panel, Unmanned Aircraft Systems Advisory Group (UAS-AG), and Unmanned Aircraft System Task Force/Working Group (UAS-TF/WG) in the Legal Committee[36]. In Germany, the Volocopter VC200 was granted provisional certification from German Ultralight Flight Association as an ultralight aircraft, which provided a basis for a public test in Dubai. Also of note, Dubai has mandated a remote identification and tracking technology, Skytrax.

Another consideration in the regulatory landscape is the level of independence of the regulatory frameworks within specific countries. In this instance, independence is described as the degree to which the individuals overseeing compliance are independent from the product development process.

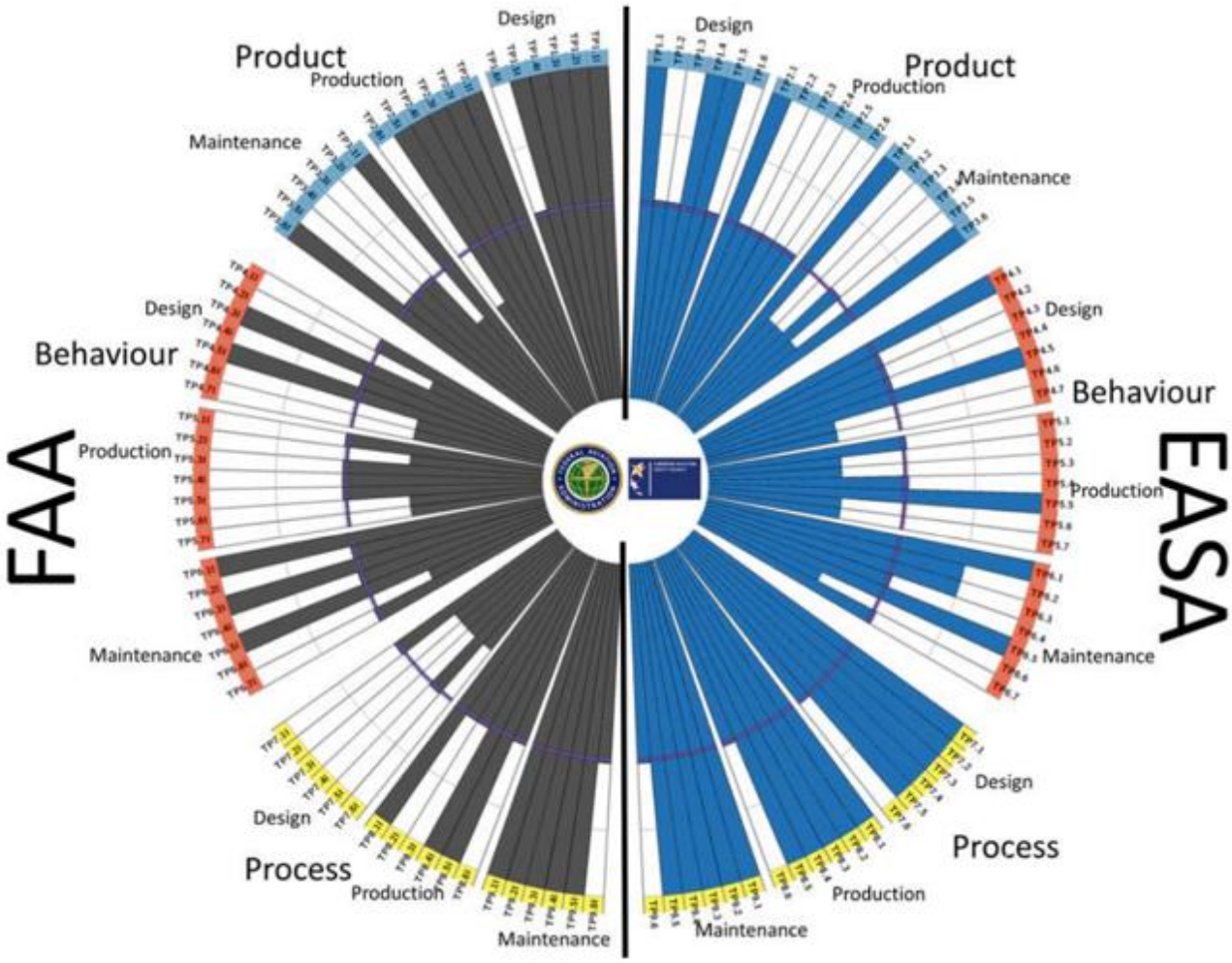
Figure 12 compares the EASA and FAA regulatory frameworks. FAA has more independent Product Certification. Airworthiness relates to multi dimensions of framework including Process, Product, and Behavior. The level of independence may influence decision of where to certify. For reference, the Independence Levels are defined as follows:

- "5 – An independent regulatory organisation or person with authority underpinned by Government legislation. Alternatively, the regulatory organisation or person is fully independent from the owner/operator with independent lines of command. They are an external regulator.
- 4 – A regulatory organisation or person who is as independent as possible from the owner/operator, but still within the owner/operator lines of command. They are an internal regulator.
- 3 – A management organisation or person removed from the task/attestation development.
- 2 – A supervisor, organisation or a person who is independent from the task/attestation development.
- 1 – A person charged with the responsibility for performing the task, the practitioner."

FAA, EASA, and NATO airworthiness share many common elements and standards. Significant standards differences (SSD) exist and are described in SSD documentation[37]. For example, comparison of EASA CS-25 and FAA Part 25 Proof of Structure terminology reveals a key wording difference, which has resulted in different interpretations on the need for and the extent of static strength testing, including the load level to be achieved. The NATO Standardization Agreement (STANAG) 4702 is based on Parts 23, 27, and CS-23. CS-VLA has similarities to PART 21.17B. Draft STANAG 4746 is based on EASA Essential Airworthiness and is harmonized with STANAG 4703. STANAG 4746 and 4703 use EASA CS-VLR as a basis. CS-E shares similar standards to Part 33, and testing covers all thrust ratings. CS-P shares similar standards to Part 35, including demonstration that the propeller can withstand the impact of a 4-pound bird for all airplanes. International type certifications are compared in Table 3 below.

[36] ICAO Legal Committee – 37th Session (Sept. 2018). *Establishing UAS Task Force/Working Group within the Legal Committee*. Doc. LC/37-WP/2-2 13/7/18.

[37] EASA and FAA Comparison. https://www.easa.europa.eu/document-library/bilateral-agreements/eu-usa/easa-significant-standards-differences-ssd-between-cs-codes-and-faa-14-cfr-codes. (Accessed on Nov. 14, 2018).



Independence Metric	
External Regulator / Legislation	5
Internal Regulator	4
Manager	3
Supervisor	2
Practitioner	1

Figure 12: Comparison for FAA and EASA Regulatory Framework Independence Metric

Table 3: International Type Certification Comparison[38]

	Fixed Wing	Rotary	Hybrid or Special	Engines	Propellers
FAA	**Part 21** – Certification Procedures for Products and Parts **Part 23** – Small Fixed Wing **Part 25** –Transport Category Airplanes	**Part 27** – Small Rotorwing **Part 29** – Transport Category Rotorcraft	**Part 21.17(b)** – Designation of applicable regulations	**Part 33** – Aircraft Engines	**Part 35** – Aircraft Propellers
EASA	**CS-22-**Sailplanes and Powered Sailplanes **CS-23**- Normal, utility, aerobatic, and commuter aeroplanes **CS-25** – Large Aeroplanes	**CS-27** – Small Rotorcraft **CS-29** – Large Rotorcraft	**CS-VLA-** Very light aircraft **CS-VLR**- Very Light Rotorcraft	**CS-E** - Engines	**CS-P -**Propellers
NATO	**STANAG 4671** – UAV System Airworthiness Requirements (USAR), Fixed wing aircraft weighing 150kg to 20,000 kg **STANAG 4703** – Light unmanned aircraft systems	**STANAG 4702** – Rotary wing unmanned aircraft systems	**Draft STANAG 4746-** Vertical Take-off and landing (VTOL)	Referenced in **STANAG 4703** **STANAG 3372**	Referenced in **STANAG 4703**

[38] CS-E vs Part 33. https://www.faa.gov/aircraft/air_cert/design_approvals/engine_prop/engine_prop_regs/engine_prop_tvalidation/media/SEI_Turbine_Engines_List_14_CFR_33_and_CS-E.pdf. (Accessed on Nov. 14, 2018); CS-P vs Part 35. https://www.faa.gov/aircraft/air_cert/design_approvals/engine_prop/engine_prop_regs/engine_prop_tvalidation/media/SSD_Propellers_List_14_CFR_35_Amdt_9_and_CS-P_Amdt_1.pdf. (Accessed on Nov. 14, 2018).

7.5.3 Domestic UAM Certification Landscape

UAM aircraft may vary in weight, type of service, propulsion, number of passengers, and speed, which may change their path to certification. New aircraft designs for UAM may have multiple paths to certification with FAA, as depicted in Figure 13. The traditional Part 21.17(a) method can be used for aircraft that fall within existing categories. Additional requirements and special conditions may apply. For example, aircraft certifying under Part 23 or 25 must also comply with Part 33 Engine and Part 35 Propeller if applicable. For aircraft that do not fall into existing categories, Part 21.17(b) may be used. This path is not meant for mass production, so eventually an update to the regulatory framework may be needed for large-scale UAM deployments for aircraft that take this path.

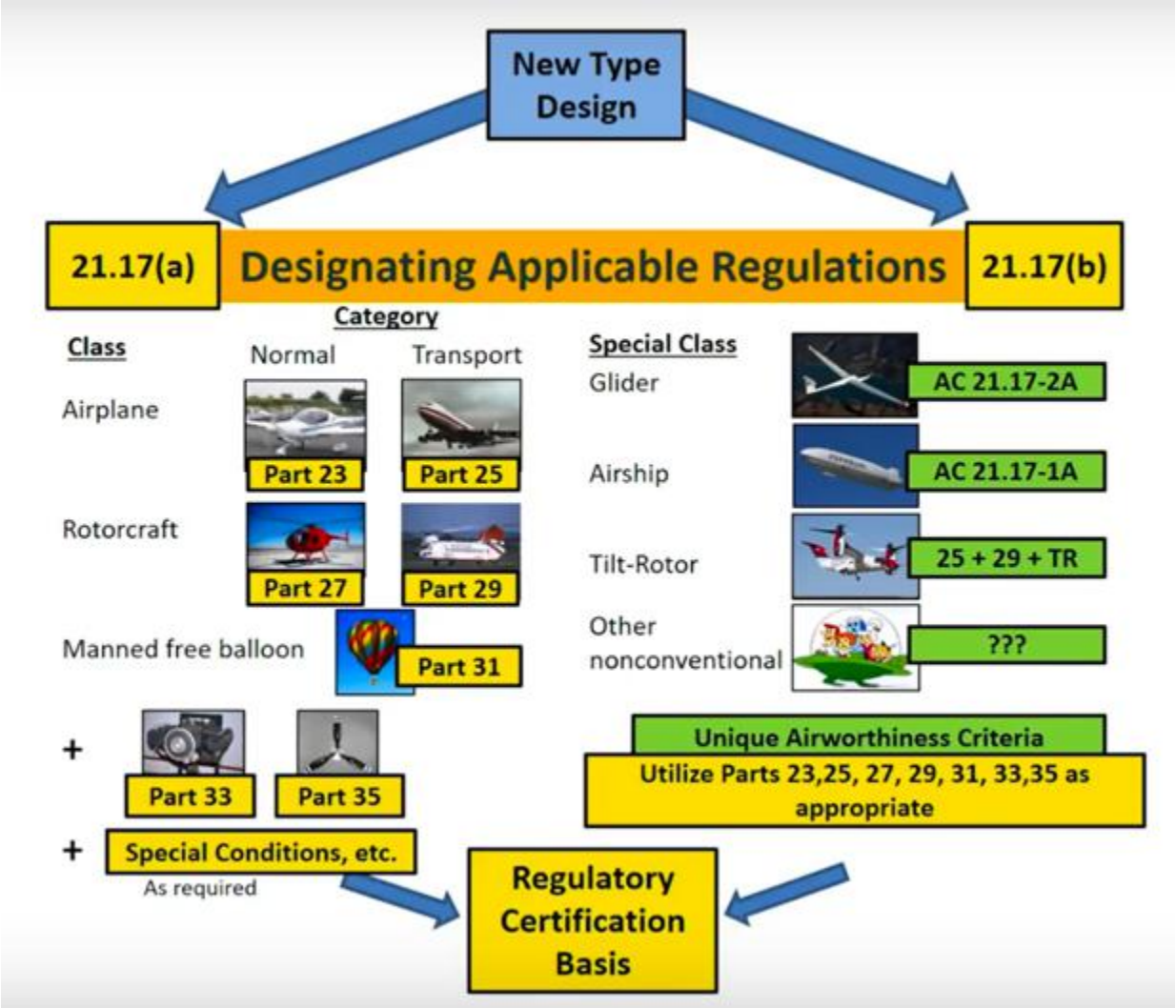


Figure 13: Paths to FAA airworthiness certification[39]

The General Aviation Manufacturers Association (GAMA) suggests that there are "regimes" for certification paths based on an aircraft's likeness to a wing-borne aircraft or a rotorcraft (Figure 14). Some examples of where typical aircraft might fall on this spectrum:

[39] Webber, David of FAA (May 2018. Time 1:28:20). *Flight Qualification and Certification of Advanced VTOL Aircraft*. Vertical Flight Society 74th Annual Forum, https://www.youtube.com/watch?v=JJf4u4MTiFs&feature=youtu.be.

- Cirrus SR22: Part 23, with Part 33 engine, Part 35 propeller
- Bell 429: Part 29 with Part 33 powerplant
- AgustaWestland AW609: Part 21.17(b)

UAM platforms targeting the *Special* class may consider using standards from the following:

- Multiple: 21.187
- Limited Category: 21.189
- Experimental: 21.191 (R&D, Exhibition)
- Experimental: 21.193 (General)

Figure 14: Range of certification approaches for hybrid fixed wing and rotary aircraft[40]

The FAA is constantly reviewing and updating this regulatory framework. For example, there are three experimental type certification projects underway ranging from 10 to 6000 lbs., including manned and unmanned. Part 23 Amendment 64 was updated Aug 2017 to provide higher level requirements and allow industry consensus standards to fill in the more detailed requirements. The amendment reduced 377 regulations to 71. The FAA recently came out with Order 8000.71 that defines Hybrid Lift as a vehicle with VTOL capabilities and uses wings during horizontal flight.

7.5.4 FAA Part Certification Process

The type certification generally follows the process depicted in Figure 15, and principles and best practices for efficient design approval processes of type certification and design are discussed in the source document. The duration and exact process details can differ by Part Regulation. For example, Part 23 generally freezes current regulations for the applicant for 3 years, while Part 25 freezes regulations for 5 years.[41] Organizational Designation Authorizations (ODA) and Designated Engineering Representative (DER) serve as representatives to oversee the certification process ensure that the applicant meets the 'airworthy' term

[40] GAMA (AHS TVF Workshop, Jan. 2018). *Path to Certification*. https://vtol.org/files/dmfile/13-TVF5-2018-Gunnarson-ASTM-Jan191.pdf.

[41] Thurber, Matt (Dec. 2006). *The Aircraft Certification Process*. https://www.ainonline.com/aviation-news/aviation-international-news/2006-12-18/aircraft-certification-process#.

as defined by FAA Order 8130.2. The ODA and DER assess compliance from *Standard* or *Special* certification request, as defined by 14 CFR 183, Order No 8100.8D. Technical standards (RTCA, SAE, ASTM, etc.) can provide means of compliance.

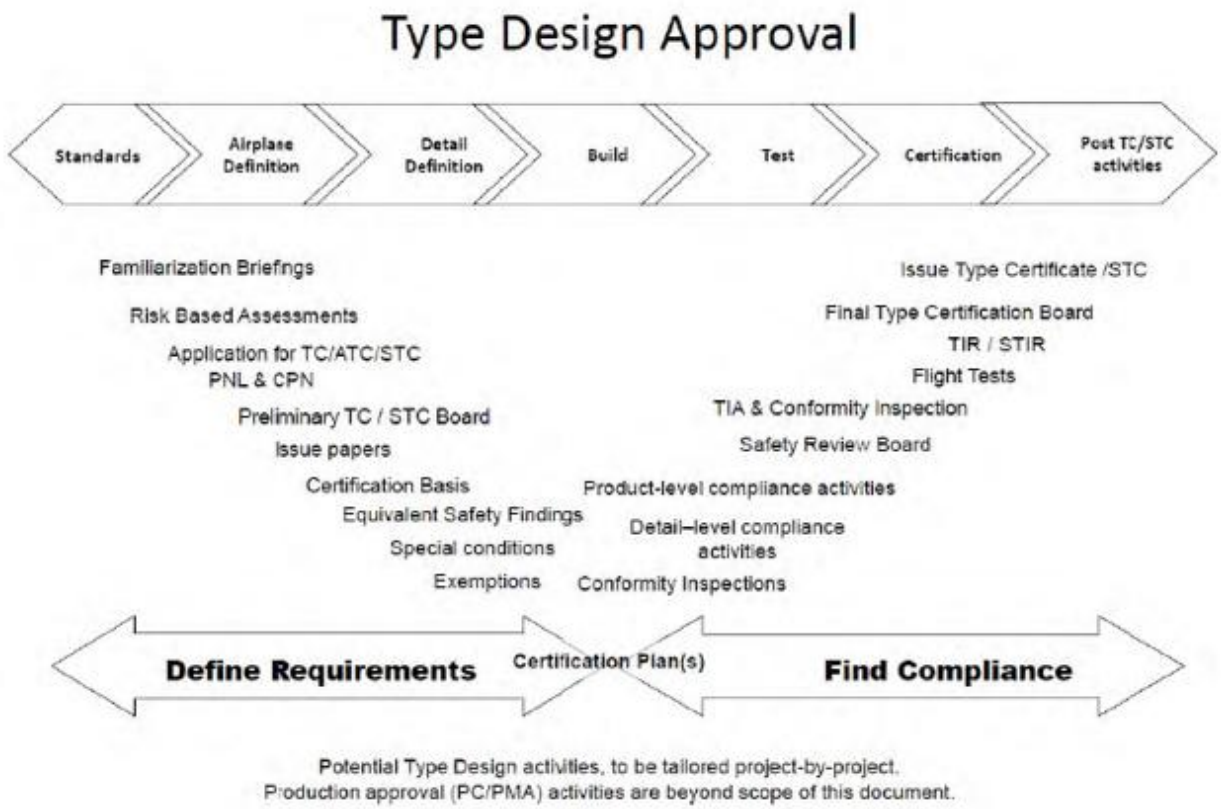


Figure 15: The type design approval process[42]

A draft summary of the Part 21.17(b) certification process for UAS is summarized in Figure 16. The Safety Risk Management (SRM) is applied by the FAA when developing regulations. The FAA uses the information and data supplied by the approval holders and other sources to develop airworthiness regulations under this certification process. The process is driven by identifying risks, which may be based on the aircraft and its intended operation, typically organized by classification. Safety requirements are transformed into risk controls for a product or article. A safety requirement in the form of an airworthiness regulation is a safety risk control that, when complied with, constitutes acceptable risk. Airworthiness Regulations are developed when systematic hazards are discovered and the related outcome(s) have unacceptable risk. Acceptable level of risk is determined as part of the rulemaking process and summarized in 25.561 per Amendment 25-64. There may be aspects of existing regulatory requirements that cannot be clearly applied to new designs. There may also be new risks that must be addressed through new requirements. For example, Part 33 Engines is written with references to piston or turbine engine, so we will need to determine how electric motors will be handled. This leaves questions about what requirements apply, and what are potential means of complying with requirements. This may require developing new means of compliance (e.g., technical standards or regulation).

[42] AIA, AEA, GAMA, and the FAA Aircraft Certification Service and Flight Standards Service (May 2017). *The FAA and Industry Guide to Product Certification*, Pg. 15. https://www.faa.gov/aircraft/air_cert/design_approvals/media/CPI_guide.pdf.

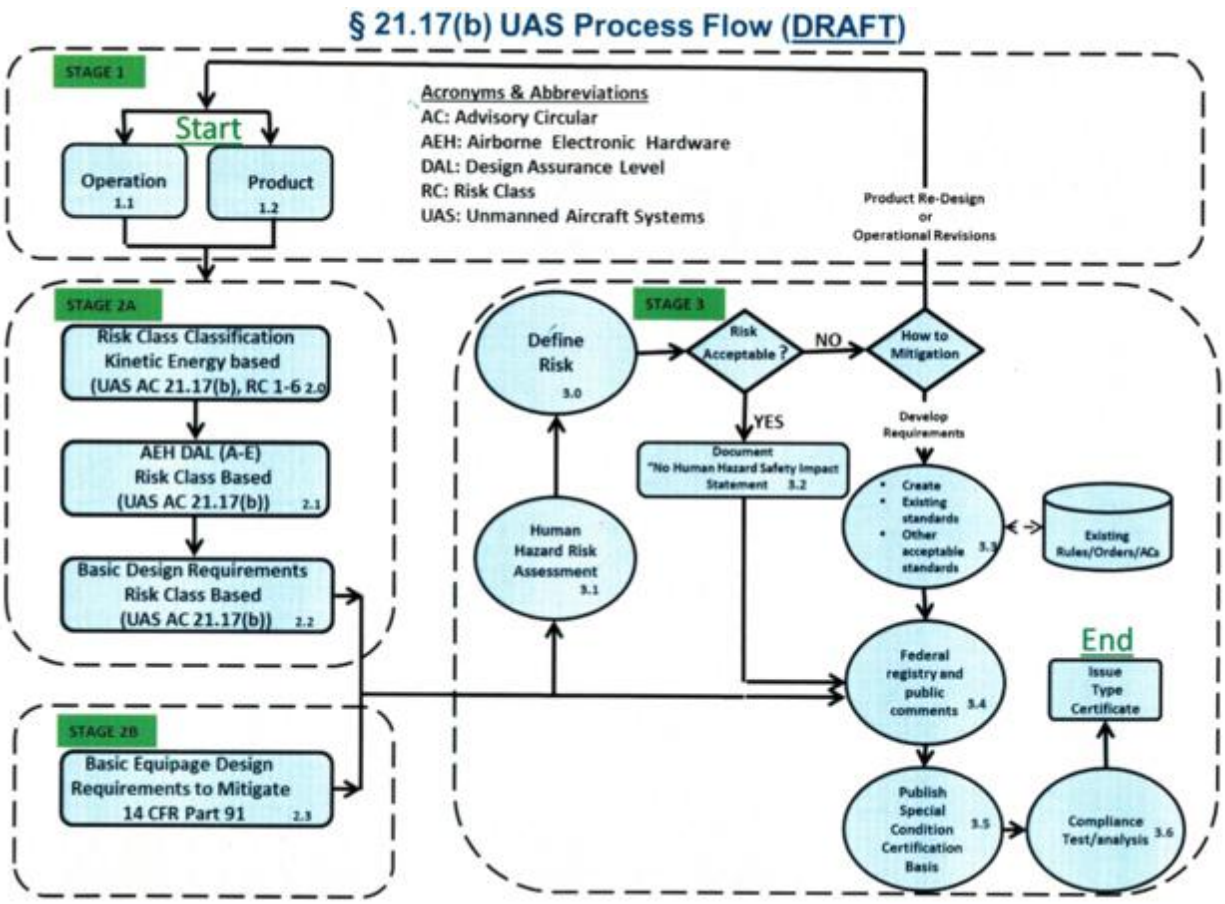


Figure 16: Part 21.17(b) certification process[43]

7.5.5 How Consensus Standards Support Certification: Means of Compliance

A requirement set forth in regulation may be met through more than one means of compliance that may include regulation, advisory circulars, or consensus standards. Figure 17 shows a set of requirements from Part 23, and an acceptable means of compliance through ASTM standards. Some Part regulations depend more on industry standards than others. For example, the Part 23 Amendment 64 shifted from prescribing detailed regulatory requirements to prescribing high-level requirements. It does not prescribe specific technical solutions nor does it have tiers or categories. Many in the aviation community see this as an opportunity to develop detailed design standards through consensus standards for flight characteristics, performance, operating limits, structures, design, powerplant, propulsion, and energy storage.

Consensus standards could accelerate UAM certification through the following activities:

- Making tiers where it makes sense
- Providing specific technical solutions
- Providing test specifications
- Providing specific compliance methods

[43] Gunnarson, Tom (Jan. 19, 2018). *Aircraft Type Certification Considerations Urban Air Mobility*. https://vtol.org/files/dmfile/13-TVF5-2018-Gunnarson-ASTM-Jan191.pdf.

Part 23 Accepted Means of Compliance Based on ASTM Consensus Standards
Updated May 11, 2018

Part 23 Rule		Accepted MOC[1]			Potential Supplemental MOC[2]
Section	Title	ASTM Standard	FAA Changes		and additional notes
23.2135	Controllability	F3264-17, Section 5.8	Replace:	With:	
			ASTM F3173/F3173M-17, Sections 4.9.1.1 and 4.9.1.2	FAA 4.9.1.1 and 4.9.1.2: 4.9.1.1: "For a level 1 or 2 airplane, or level 3 or 4 airplane of 6,000 pounds or less maximum weight, 5 seconds from initiation of roll and" 4.9.1.2: "For a level 3 or 4 airplane of over 6,000 pounds maximum weight, (W+500) / 1300 seconds, but not more than 10 seconds, where W is the weight in pounds."	
			ASTM F3173/F3173M-17, Sections 4.9.3.1 and 4.9.3.2	FAA 4.9.3.1 and 4.9.3.2: 4.9.3.1: "For a level 1 or 2 airplane, or level 3 or 4 airplane of 6,000 pounds or less maximum weight, 4 seconds from initiation of roll and" 4.9.3.2: "For a level 3 or 4 airplane of over 6,000 pounds maximum weight, (W+2,800) / 2,200 seconds, but not more than 7 seconds, where W is the weight in pounds."	
23.2140	Trim	F3264-17, Section 5.9	None		
23.2145	Stability	F3264-17, Section 5.10	None		
23.2150	Stall characteristics, stall warning, and spins	F3264-17, Section 5.11	None		

Figure 17: Sample means of compliance from Part 23[44]

7.5.6 Current Standards Provide Means of Compliance

This section provides a sample of some RTCA, SAE, and ASTM standards that support means of compliance. These standards support aspects such as design, testing, testing tools, software considerations, and verification. We have included some standards non-specific to aircraft that may potentially inform UAM certification such as SAE work on testing automated driving systems, which includes work on validation and verification and test scenarios that address identified risks for autonomous systems.

Many of these means of compliance may continue to support UAM aircraft, however some will be inadequate. The **bolded text** illustrates standards needed to enable UAM, and that may prove to be challenging to which to certify. For example, a clear standard regarding software and integrated equipment onboard UAM aircraft will need to be identified for manufacturers and certification entities to enforce. Modifications to the aircraft certification heavily rely on guidance from a regulatory body.

RTCA: Example RTCA standards that relate to UAM:

- **DO-160** - Environmental Conditions and Test Procedures for Airborne Electronic/Electrical Equipment and Instruments
- **DO-178C** - Software Considerations in Airborne Systems and Equipment Certification
- **DO-254** - Design Assurance Guidance for Airborne Electronic Hardware
- **DO-362** - Command and Control (C2) Data Link Minimum Operational Performance Standards (MOPS)(Terrestrial)

[44] *Part 23 Accepted Means of Compliance Based on ASTM Consensus Standards* (May 11, 2018). https://www.faa.gov/aircraft/air_cert/design_approvals/small_airplanes/small_airplanes_regs/media/part_23_moc.pdf.

- **DO-365** - Minimum Operational Performance Standards (MOPS) for Detect and Avoid (DAA) Systems
- **DO-366** - Minimum Operational Performance Standards (MOPS) for Air-to-Air Radar for Traffic Surveillance
- **DO-278** – Software Integrity Assurance Considerations for Communication, Navigation, Surveillance, and Air Traffic Management (CNS/ATM) Systems

- Supplement DOs (used as applicable):
  - **DO-248C** - Supporting Information for DO-178C and DO-278A
  - **DO-330** - Software Tool Qualification Considerations
  - **DO-331** - Model-Based Development and Verification Supplement to DO-178C and DO-278A
  - **DO-332** - Object-Oriented Technology and Related Techniques Supplement to DO-178C and DO-278A
  - **DO-333** - Formal Methods Supplement to DO-178C and DO-278A

  Examples of ongoing activities:
  - **SC-228 -** Minimum Ops Performance Standards for UAS
  - **SC-214** - Air Traffic Data Communications
  - **SC-186** - ADS-B

SAE: Example SAE standards that relate to UAM:

- **ARP-4761** - Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment; In conjunction with ARP4754, ARP4761
- **ARP-4754A** - Certification Considerations for Highly-Integrated or Complex Aircraft Systems
- **ARP94910 Aerospace** - Vehicle Management Systems - Flight Control Design, Installation and Test of, Military Unmanned Aircraft, Specification Guide For
- **ARP6461** - Guidelines for Implementation of Structural Health Monitoring on Fixed Wing Aircraft
- **AS-1212** – Electric Power, Aircraft, Characteristics, and Utilization

Leveraging of standards efforts in other domains may be beneficial, such as:

- **SAE J3016**: Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems – known for the "5 Levels of Automation."
- **SAE J3092**: Dynamic Test Procedures for Verification & Validation of Automated Driving Systems (ADS)

ASTM: Example ASTM standards that relate to UAM:

- **F3264-17** - Standard Specification for Normal Category Aeroplanes Certification
- **F3201 – 16 -** Standard Practice for Ensuring Dependability of Software Used in Unmanned Aircraft Systems (UAS)
- **F3269 – 17** - Standard Practice for Methods to Safely Bound Flight Behavior of Unmanned Aircraft Systems Containing Complex Functions

- **F3298 – 18** - Standard Specification for Design, Construction, and Verification of Fixed-Wing Unmanned Aircraft Systems (UAS)
- **F2295-10** – Standard Practices for Continued Operational Safety Monitoring of a Light Sport Aircraft
- **F39.05** Standard Practice for Design and Manufacture of Electric Propulsion Units
- **F44.40** Powerplant

Examples of ongoing activities:

- Committee F38, F39, F44

7.5.7 Gaps in Standards

Efforts are underway to identify and address gaps in standards for emerging technologies that relate to UAM. In particular, ASTM F38 on Unmanned Aircraft Systems conducted a gap analysis for UAS that is particularly informative as shown in Figure 18. Gaps were identified in relation to Airframe, Power Plant, and Avionics in three overarching categories of certification: Airworthiness, Operations, and Crew Qualifications.

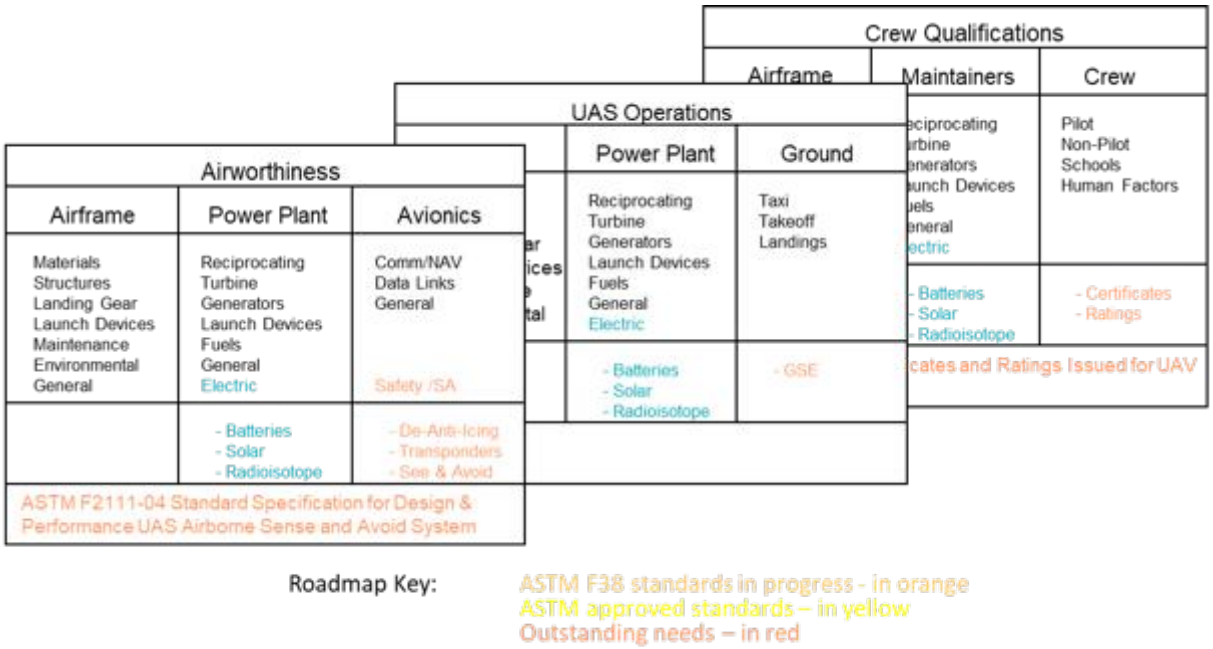


Figure 18: Sample results from the ASTM F38 standards gap analysis for UAS[45]

7.5.8 Potential Gaps in Means of Compliance for UAM: General and Propulsion/ Energy Storage

Table 4 details some of the standards gaps in detail and captures efforts underway that may help create a viable path to certification for UAM. The functional hazards arise from the need to better understand the potential hazards of the technology and use case. One example of ongoing work in this space is with automated driving systems. ISO-26262 is a functional safety standard that follows systems engineering processes to address functional safety of vehicles, but this framework. ISO 21448, Safety of the Intended Function (SOTIF) is a new standard being developed to support vehicle automation. Risk assessment is a challenge, which stems from new flight modes and characteristics. For new technologies, sometimes these are identified through scenario analysis, such as for the BNSF EVLOS risk analysis. Note that it can be

[45] ASTM. *UAS Standards Gap Analysis*. Committee F38.

challenging to assess progress of these efforts, as standards organizations do not typically share works in progress.

Table 4: Summary of key standards, gaps, and activities

Requirement	Relevant Documents	Gap	Relevant Activities
All Aircraft: Functional Hazards	FAA 23.1309-1E, AR 70-62, MIL-HDBK-516C	Identification of hazards, design methods to address hazards, and testing methods	ISO-21448 SOTIF
All Aircraft: Risk Assessment and Management	FAA Order 8040.4A, SAE ARP 4761, MIL-STD-882E	New flight modes and characteristics, unclear risk profiles	
Part 33/ CS-E: Electric Propulsion	ASTM F39.05 *Electric Propulsion Units*	Design and manufacture issues	Proposed Revision (WK47374)
Part 33/ CS-E: Electric Propulsion	ASTM F44.40 *Powerplant*	Integration issues for hybrid-electric propulsion	Proposed Revision (WK41136)
Part 33/ CS-E: Electric Propulsion	ASTM F39.05 *Electric Propulsion Units*	Energy storage systems	Proposed Revision (WK56255)
All Aircraft: Software Design Assurance	RTCA DO-178C	The methods are unable to handle the large number of states and decisions that autonomy algorithms can take	
Detect and Avoid (DAA)		Minimum Operational Performance Standards (MOPS) to specify DAA equipment to support BVLOS UAS operations in Class D, E, and perhaps G, airspace.	RTCA SC-228
Command and Control (C2)	RTCA DO-362	Normative performance standards for C2 link systems and constituent subsystems, including beyond radio line of sight (BRLOS).	

There may be some gaps in the certification process where specific approaches and tools need to be developed, particularly along system redundancy and failure management. There is an increasing awareness of current gaps, and potential strategies for certification for UAM. This was recently discussed at a Congressional hearing on 7/24/2018[46].

- **Autonomous and highly complex software** - Software is becoming increasingly complex. Machine learning and other algorithms used for automation are non-deterministic, which means that even for the same input, the algorithm may exhibit different behaviors on different runs. This problem is not specific to aviation and falls under the broader topic of explainable and verifiable artificial intelligence (AI). It is considered a major challenge worthy of significant investment at the National Science Foundation (NSF), Defense Advanced Research Projects Agency (DARPA), and USDOT to name a few.

- **Distributed electric propulsion/ Electric powerplant -** Both propulsion and energy storage pose challenges in an industry that has traditionally worked with engines and liquid fuels. The failure modes will look different. How will multi-copters handle prop failures, motor failures, electrical system failures, and energy storage failures? What redundancies and mitigation measures are needed?

- **Unmanned/ optionally piloted** - The end goal for many UAM business models is to have these aircraft operate without an onboard pilot. Zee Aero is targeting certification for optionally piloted UAM. Because of the operational risks, there are additional airworthiness requirements. There is considerable work going on in the UAS domain attempting to address these challenges, which UAM may benefit from, but the UAM use case may still generate specific requirements.

- **Ratio of Aircraft to Operators < 1** - Several UAM business models include a transition period to full autonomy that may include operations centers with remote operators controlling multiple aircraft. The operational risk of this use case will need to be considered in airworthiness. The FAA is holding a meeting in September that I am attending that will explore potential impacts of multiple operations.

7.5.9 Potential Certification Approaches for Air Taxi and Air Ambulance

Potential certification approaches for Air Taxi and Air Ambulance markets depends on vehicle characteristics and intended use. There are a range of UAM concepts and some may be closer to a fixed wing (e.g., Part 23) or a rotary craft (e.g., Part 27) depending on their configuration, as depicted in Figure 19.

There will be challenges in determining which of the existing FAA certification standards apply to the types of vehicles being considered for the Air Taxi or Air Ambulance UAMs, and/or how existing certification standards can be met or should be amended.

Air Taxi UAMs: Given their sizes, they could be compared to “light civil”, which would be FAA Part 23 (normal airplanes) or a Part 27 (normal rotorcraft). However, given the mission of passenger transport, it could be argued that Part 25 (airplane) or Part 29 (rotorcraft) could apply. Part 23 Amendment 64 may be an attractive option if industry consensus standards can be developed to appropriately tier UAM platforms, define technical solutions, test methods, and means of compliance. If existing categories are insufficient, Part 21.17(b) offers certification for special aircraft, which may include leveraging elements from multiple categories in the existing airworthiness regulatory framework, as well as defining new requirements.

Air Ambulances UAMs: In addition to the certification standards listed above for Air Taxis, Air Ambulance UAMs will require detailed guidance for the evaluation of an operator’s air ambulance procedures, specific

[46] House Committee on Science, Space, and Technology (July 24, 2018). *Full Committee Hearing - Urban Air Mobility – Are Flying Cars Ready for Take-Off?*. https://www.youtube.com/watch?v=2US-SoC8wibA.

sections of their General Operations Manual (GOM) related to air ambulance, and the unique requirements an operator must meet prior to being issued Operations Specification (OpSpec) for Helicopter, Airplane, or a new category depending on how the UAM is classified.

The question of classification is critical. The certification path will influence time to market and associated costs. Part 23 may offer more flexibility due to its extensive use of industry consensus standards – but those standards still need to be developed. We also discussed the potential for Part 21.17(b) for special aircraft, which may borrow portions of 23 and 27, but this is not meant for mass production.

This space is continuing to evolve. FAA has Type Certification projects ongoing. ASTM is identifying and addressing standards gaps. International entities are taking the lead on experimenting with new UAM certification (e.g., Volocopter).

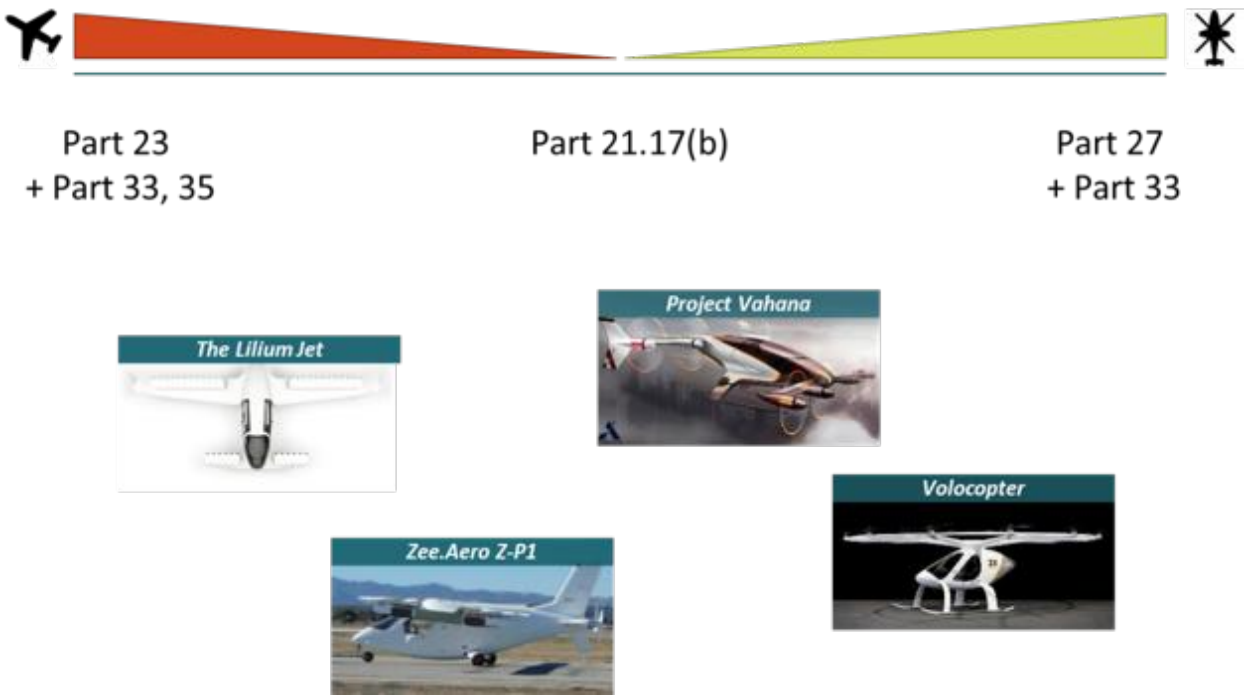


Figure 19: UAM concept vehicles may fall along a spectrum ranging from resembling fixed wing or rotary aircraft

7.5.10 Enabling Strategies

As this space evolves, it may be helpful to develop roadmaps for certification paths, gaps, and needs for the various UAM sizes and use cases. The FAA UAS Integration Office recently started developing a roadmap, but it is currently unclear how the outputs will benefit the UAM market. Tracking progress of international entities could help build a more complete picture of gaps and efforts to address those gaps. For example, opportunities for coordination and collaboration may exist. Tracking developments in the automated vehicle space may inform the development of test methods, software considerations, and risk frameworks. While this report focused on airworthiness, that is only part of the certification challenges. There are many important challenges in the areas of operator (crew) and operations certification that will need to be addressed as well.

7.6 Legal and Regulatory Summary

Key Findings

Legal, regulatory, and certification challenges and opportunities exist in order to bring UAM to the market. The analysis on UAM draws a comparison to the UAS legal and regulatory achievements as many of the UAM areas are being addressed to some extent with the emergence of UAS operations. Similarly, UAS research has helped reduce the gap towards enabling UAM. Some of the challenges involve the dynamic legal environment which include many unresolved challenges, especially establishing where federal, state, and local authorities take lead. Additionally, UAM poses legal challenges that touch on most aspects of aviation, especially in the areas of air traffic control and management, and flight standards, but also environmental policy, public use, land use, and local restrictions. However, the current legal framework is starting to evolve to match the technology, especially in light of the FAA Reauthorization Act of 2018. That being said, assured autonomy remains a challenging technical and legal problem.

Moreover, a diversity in approaches exists whereby States and locales are undertaking legal experiments through a mix of approaches, ranging from designating UAS launch sites to hyperlocal restrictions. Additionally, State and local laws range from laws prohibiting drones to laws protecting UAS operations. Similarly, diverse regulations have appeared internationally as well.

With respect to certification, many efforts are underway at FAA, ASTM, RTCA, SAE, and elsewhere to provide methods of aircraft certification for UAM, but there is still no clear certification path and several gaps in means of compliance. However, opportunities may exist to:

- Develop a roadmap to airworthiness that considers the range of potential UAM aircraft and paths to certification.
- Study and leverage international efforts (e.g., ICAO, EASA, NATO).
- Study and leverage efforts from similar domains, such as autonomous cars (e.g., SAE Validation and Verification Task Force).
- Explore other certification challenges for operator and operations certification.

More importantly, however, are the strategies which currently exist to help the UAM technology move forward. Enabling strategies can be employed to accelerate the development of a UAM legal framework such as:

- NASA – FAA cooperation, such as the Research Transition Team
- FAA Aviation Rulemaking Committee
- FAA UAS Integration Pilot Program
- Leveraging strategies from automobile automation, such as voluntary standards may help UAM deployment
- FAA Reauthorization act of 2018 provides much needed support for industry and ensuing economy

8.0 SOCIETAL BARRIERS

Research on the potential societal barriers of an emerging technology is important to understanding the potential viability of the technology from a societal perspective, opportunities and challenges associated with markets, use cases, business models, and partnerships. Research on societal barriers can also provide insight on the potential impacts of deployment. Additionally, research on societal barriers can help identify early technological, market, or consumer challenges to address, such as how UAM can be used to improve airport access or reduce commute times. Societal barriers research can also help provide a predictive understanding of supply and demand patterns, such as willingness to use a technology or service and under what conditions. Finally, societal barriers research can be employed to help inform public policy to help maximize the potential benefits and minimize potential adverse effects of a technology.

Unfortunately, regional and national travel surveys do not include predictive questions to forecast modal shift and other transportation impacts resulting from emerging transportation technologies and service. In an effort to study the potential societal impacts of innovative and emerging transportation innovations, researchers often propose hypotheses before a technology/service has been tested. They may collect and analyze prospective data by employing focus groups, surveys, scenario analysis, and other quantitative and qualitative methods (e.g., simulators, drive clinics, etc.). After a technology has been deployed, researchers will likely propose additional hypotheses, performance metrics, and data sources for evaluation. Figure 20 introduces the steps to conducting research on Societal Barriers.

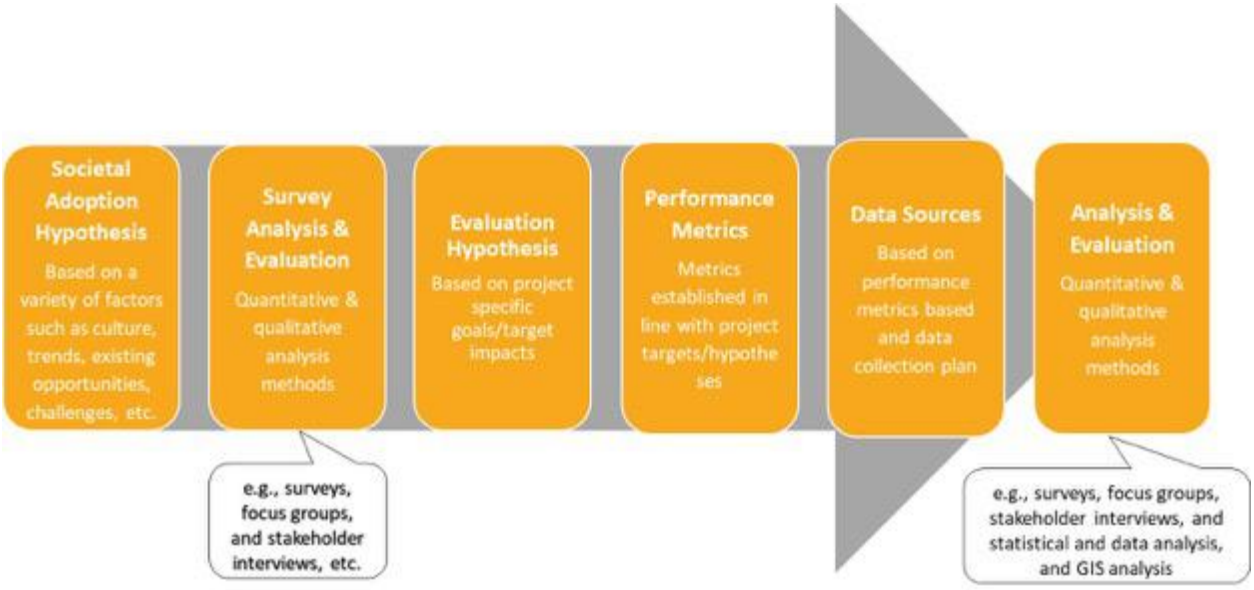


Figure 20: Research Process for Societal Barrier Studies

For this study, we conducted three key steps to study the potential societal adoption of UAM. First, we conducted a literature review on existing studies that examine trust in automation, perceptions of UAM and other related technologies, and feelings toward the composition and characteristics of flight crews (e.g., gender perceptions, etc.). We then conducted two focus groups to collect qualitative responses and help inform the development of a general population survey regarding UAM across five U.S. cities. Two focus groups were completed in June 2018 in Washington, D.C. and Los Angeles. The participants of the focus groups were engaged on topics such as: familiarity with UAM; their thoughts and impressions of UAM; and views regarding ownership, automation, and safety. In August 2018, we completed an exploratory general population survey consisting of approximately 1,700 respondents in Houston, Los Angeles, New York, San Francisco, and Washington, D.C. (approximately 350 respondents per city). The survey expanded on the topics covered in the focus groups and included additional questions about willingness-to-fly, weather, and noise concerns. The literature review, focus group, and survey findings are each reviewed in the following sections.

8.1 Literature Review

Increased urban congestion, airborne technology innovation, and autonomous technology advancements have prompted research into UAM as a possibility for future transportation. Our study aimed to identify societal barriers facing UAM through questions targeting several themes: 1) preferences for piloted, remotely piloted, or automated UAM; 2) technological preferences for UAM aircraft, such as fixed wing vs. vertical takeoff and landing aircraft or electric vs. gasoline aircraft; 3) noise and aesthetics of aircraft; 4) the use of UAM aircraft over certain land uses, such as residential neighborhoods; and 5) perceptions of UAM sharing and ownership. This literature review provides background on existing literature, much of which covers the topics of trust in automation; initial perceptions of automated and unmanned flight; and preferences for cockpit configurations. First, we briefly review the concept of trust before diving into several studies that examine trust in automated systems (i.e., automated medical systems, automated vehicles, autonomous aircraft). The literature review also details several studies examining the introduction of UAM as a new mode of travel and perceptions of automated vs. piloted flight.

8.1.1 Trust and Automation

Trust is a necessary component of gaining public support for an emerging technology. Care should be taken to understand the implications of trust on UAM public acceptance. In a study of organizational trust, Mayer, Davis, and Schoorman (1995) made the case that trust is a "psychological construct" associated with relinquishing control of a situation to another person or object under the assumption that the situation will be executed safely and well.[47] For UAM deployment to succeed, the industry will need to gain the public's trust and convince them that travel using UAM aircraft will be safe and reliable. However, trust is fragile, and can be lost and never regained after a bad experience (Slovic, 1993).[48]

UAM confronts many similar challenges to automated vehicles in building public trust. Automated vehicle (AV) success largely hinges on public support and adoption. A study by Anania et al. (2018a) found that associating AVs with positive or negative information strongly impacts consumer support.[49] When participants in the study were presented with media headlines that contained negative information about AVs, they were less willing to ride in driverless vehicles. Likewise, when participants were presented with positive information, they were more willing to ride in driverless vehicles than before they had been exposed to the headlines.

For this study, the willingness-to-fly scale developed by Winter et al. (2015) was adapted to measure willingness to ride in AVs.[50] This is the same scale that we adapted for our study to measure willingness to use UAM. In addition to the different automated technology studied (AVs vs UAM), the study by Anania et al. (2018a) measures responses to full automation[49], while our study aimed to measure willingness for varying degrees of automation. In addition to positive and negative information exposure, the reliability of automated systems factors highly in consumer trust. Drops in reliability tend to degrade trust in automated systems, in turn leading to negative performance assessments and decreased adoption. Support for robot

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[47] Mayer, R. C., Davis, J. H., & Schoorman, F. D. (1995). An integrative model of organizational trust. *Academy of management review*, *20*(3), 709-734.

[48] Slovic, P. (1993). Perceived risk, trust, and democracy. Risk analysis, 13(6), 675-682.

[49] Anania, E. C., Rice, S., Walters, N. W., Pierce, M., Winter, S. R., & Milner, M. N. (2018a). The effects of positive and negative information on consumers' willingness to ride in a driverless vehicle. Transport Policy.

[50] Winter, S. R., Rice, S., Mehta, R., Cremer, I., Reid, K. M., Rosser, T. G., & Moore, J. C. (2015). Indian and American consumer perceptions of cockpit configuration policy. Journal of air transport management, 42, 226-231.

systems relies mainly on six factors: reliability, predictability, trust in the engineering, technical capabilities, system failures, and risk (Desai et al. 2012).[51] Our study assessed the public's perceptions of comfort and safety in regard to UAM aircraft; future research efforts could examine the effects of simulated drops in performance on the public's willingness to use UAM. Carlson et al. (2014) investigated commonalities and dissimilarities in a survey of public perception of automation in vehicles and medical systems, finding that an up-to-date system with available statistics of past performance was important in both forms of automation[52]. Respondents wanted greater levels of control and understanding of the system in the automotive domain than in the medical realm. Brand recognition was also important to respondents, as they were more likely to embrace automation from companies, such as Google and IBM, than from lesser-known or startup companies. In our study, we did not examine brand recognition but we did examine the impact of familiarity with the UAM concept on a person's willingness to use the technology.

8.1.2 UAM as an Innovative Transportation Mode

The public hesitation toward accepting AVs is reflected in studies that examine the public's perceptions of UAVs. Of note, a few authors used the term "UAVs" to refer to pilotless aircraft, even though the aircraft, per the authors' definitions may have been intended to carry passengers. Tam (2011) investigated public risk perceptions of "UAVs" to transport cargo and passengers, and found that the largest perceptions of risk involved technological reliability and higher perceived safety with a human pilot onboard.[53] The study only examined fully automated flight, but with different levels of monitoring (i.e., pilot on board, controlled from the ground, or no pilot on board). Our study examined different levels of automation, from human-piloted flight to fully automated flight. Seventy-seven percent of passengers supported automated aircraft, if a pilot was onboard to actively monitor the operation. However, 60% of surveyed passengers had little to no familiarity with UAVs (pilotless aircraft). A limitation to note with the study by TAM (2011) is approximately 53% of the 158 respondents were between the ages of 50-64; the study results might be biased towards the perceptions of particular age groups[53]. In a study by Ragbir et al. (2018), survey participants noted potential benefits of automated flight such as: decreases in pilot fatigue, human error, and lower costs for automated aircraft.[54] However, the benefits were generally outweighed by concerns over reliability; system security; lack of a human pilot; and operation under extreme conditions, such as rain, snow, and ice. Similarly, our study examines the effect of different weather conditions on user perceptions.

A variety of factors work together to influence public opinion of automated and/or unmanned flight. MacSween-George (2003) conducted a survey gaging participant interest in pilotless, automated aircraft, both for passenger transportation and goods movement.[55] While people were generally unenthusiastic about automated, unmanned aircraft, there was greater support for cargo transportation. Furthermore, educating survey participants about automated, unmanned flight led to greater support for the technology.

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[51] Desai, M., Medvedev, M., Vázquez, M., McSheehy, S., Gadea-Omelchenko, S., Bruggeman, C., ... & Yanco, H. (2012, March). Effects of changing reliability on trust of robot systems. In Proceedings of the seventh annual ACM/IEEE international conference on Human-Robot Interaction (pp. 73-80). ACM.

[52] Carlson, M. S., Desai, M., Drury, J. L., Kwak, H., & Yanco, H. A. (2014). Identifying factors that influence trust. In 2014 AAAI Spring Symposium Series.

[53] Tam, A. (2011). Public perception of unmanned aerial vehicles.

[54] Ragbir, N. K., Baugh, B. S., Rice, S., & Winter, S. R. (2018). How Nationality, Weather, Wind, and Distance Affect Consumer Willingness to Fly in Autonomous Airplanes. Journal of Aviation Technology and Engineering, 8(1), 1.

[55] MacSween-George, S. L. (2003, March). Will the public accept UAVs for cargo and passenger transportation?. In Aerospace Conference, 2003. Proceedings. 2003 IEEE (Vol. 1, pp. 1-367). IEEE.

While this survey is somewhat dated in that people associated unmanned flight and forms of UAV transportation with drones in the Afghanistan and Iraq wars, it still shows the potential power of education.

Anania et al. (2018b) found that UAV support also varies with racial bias and political leanings.[56] Participants in the study were more supportive of UAVs flying over primarily African American neighborhoods than they were of Caucasian neighborhoods. Politically conservative survey respondents were much more willing to accept UAVs than were liberal respondents. While these perceptions will likely change over time, understanding such consumer attitudes toward UAVs can better inform developers and policy makers.

A number of studies also investigated differences in perceptions on automated flight based on nationality. Ragbir et al. (2018) found that Indian survey participants were generally more accepting of automated, pilotless commercial flight than were American participants.[54] While Indian respondents supported UAV usage in all but the most extreme flight conditions, Americans only positively viewed automated, pilotless flight under near perfect conditions. While our study does not compare perceptions of UAM based on different nationalities, we will have a large sample size (~1700) of American respondents.

8.1.3 Piloted vs Automated Flight

Passengers are less willing to fly on board a solely automated aircraft than a hybrid cockpit or traditional two-pilot cockpit (Rice et al. 2014; Winter et al. 2015; Mehta et al. 2017).[57] [50] [58] Hughes et al. (2009) found that acceptance for automated flight depended mainly on trust, which in turn was largely influenced by feelings.[59] They saw that in general, though, people had a more negative view of automated cockpits and preferred a human pilot, even in cases where monetary discounts would be offered to fly in auto-pilot systems. In fact, their confidence in the automated pilot went down for cheaper flights. The participants may have assumed cost-cutting or cheaper flights would be less reliable. While our study did not examine the difference in pricing between automated and human-piloted flight, we did collect data on the effects of pricing on the willingness-to-fly in UAM.

Mehta et al. (2017) found that, given the option of flying in piloted aircraft of various configurations (male-male pilots, male-female pilots, or female-female pilots) or flying in an automated aircraft (with no human pilot in the cockpit), survey respondents were least willing to fly on automated airplanes.[58] Similar to the findings of the study by Ragbir et al. (2018), U.S. participants were less willing to fly on automated planes than were Indian participants.[54] Rice et al. (2014) saw similar results, with Americans having a more positive reaction to human pilots and a more negative reaction to automated, unmanned aircraft than did Indian passengers.[57] Trust in air traffic controllers could be used as a proxy for trust in remote pilots. Mehta et al. (2016) looked at differing support for air traffic controllers based on age, showing that Americans generally favored older air traffic controllers, while Indians were more trusting of young air traffic controllers.[60] These

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[56] Anania, E. C., Rice, S., Winter, S. R., & Milner, M. N. (2018b, April). Racial Prejudice Affecting Support for Unmanned Aerial Vehicle Operations. In Proceedings of the Technology, Mind, and Society (p. 2). ACM.

[57] Rice, S., Kraemer, K., Winter, S. R., Mehta, R., Dunbar, V., Rosser, T. G., & Moore, J. C. (2014). Passengers from India and the United States have differential opinions about autonomous auto-pilots for commercial flights. International Journal of Aviation, Aeronautics, and Aerospace, 1(1), 3.

[58] Mehta, R., Rice, S., Winter, S., & Eudy, M. (2017). Perceptions of cockpit configurations: a culture and gender analysis. The International Journal of Aerospace Psychology, 27(1-2), 57-63.

[59] Hughes, J. S., Rice, S., Trafimow, D., & Clayton, K. (2009). The automated cockpit: A comparison of attitudes towards human and automated pilots. Transportation research part F: traffic psychology and behaviour, 12(5), 428-439.

[60] Mehta, R., Rice, S., Rao, N., Coudert, A., & Oyman, K. (2016). Age and Trust in Air Traffic Controllers: A Comparison Between Two Countries.

findings help to shed light on trust in piloted and remotely piloted aircrafts, as emotional response toward air traffic controllers can mirror attitudes toward automated flight, with or without a pilot present.

Gender is also a significant factor for understanding passenger attitudes toward piloted and automated flight. Cultural biases can affect the public's perceptions of flight safety and trust in a pilot, even when there is contradictory evidence toward the accuracy of these perceptions. The public has greater support for automated flight with pilots onboard to monitor the system, so understanding the factors that drive the public's attitudes toward gender in piloted flight are important to early stage UAM adoption. McCarthy, Budd, and Ison (2015) observe that women face greater barriers than do men in flight sector participation.[61] In a passenger survey conducted in 2012, 51% of respondents reported that they were less likely to trust a woman pilot, and 32% believed men would be 'more skilled' as pilots than women (Anderson, 2013).[62] Both Walton and Politano (2014)[63] found that male pilots were more likely to hold a negative view of female pilots, unless they frequently shared flight decks with women. Walton and Politano note that studies looking at aircraft accidents, but did not find differences in accident rates by gender.[63]

Rice et al. (2015) developed a willingness-to-fly index[64] that was used by Mehta et al., (2017) to examine the ways different cultural considerations impact gender biases.[58] Metha et al. (2017) found that male Indian passengers were less willing to fly with two female pilots than were male American passengers.[58] Furthermore, Indian males had less trust in young female flight controllers than did male Americans (Mehta et al., 2016).[60]

These studies show that women face greater difficulties in working as pilots and gaining acceptance as pilots. Thus, female pilots operating UAM or serving as remote pilots may confront cultural and stereotype barriers that could impact UAM adoption. McCarthy, Budd, and Ison (2015) recommend a focus on gendered leadership differences and positive female representations as potential future solutions.

Our study on the potential societal barriers of UAM fills a number of key gaps in the literature. First, UAM differs markedly from both commercial and general aviation in terms of potential use cases, aircraft, trip types and distances, etc. Additionally, UAM also differs from unmanned aerial vehicles and drones (e.g., size of aircraft, use cases, the role pilotless technologies when no passengers are on board, and perceptions about privacy). While these studies from other aviation disciplines can provide a baseline understanding that can help shed light on potential barriers with new aviation technologies, such as UAM, actual societal acceptance could vary. Additionally, methods from these studies such as the willingness to fly scale from Rice et al. 2015 were used to help develop the survey employed as part of this study. Specific methods from the literature applied in this study are discussed in the survey methodology discussion that follows.

8.2 Focus Groups

8.2.1 Methodology

Two focus groups were conducted in June 2018 to gain insight on the potential societal barriers associated with Urban Air Mobility from both the user and non-user perspectives. One focus group was held in Arlington, Virginia and a second focus group was held in El Segundo, California. All focus groups were guided

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[61] McCarthy, F., Budd, L., & Ison, S. (2015). Gender on the flightdeck: Experiences of women commercial airline pilots in the UK. Journal of air transport management, 47, 32-38.

[62] Anderson, S. (2013, November 12). Who do you trust more, male or female pilots? Retrieved November 6, 2018, from https://www.sunshine.co.uk/news/who-do-you-trust-more--male-or-female-pilots--105.html

[63] Walton, R. O., & Politano, P. M. (2014). Gender-related perceptions and stress, anxiety, and depression on the flight deck. Aviation Psychology and Applied Human Factors.

[64] Rice, S., Mehta, R., Dunbar, V., Oyman, K., Ghosal, S., Oni, M. D., & Oni, M. A. (2015, January). A valid and reliable scale for consumer willingness to fly. In *Proceedings of the 2015 Aviation, Aeronautics, and Aerospace International Research Conference*.

by protocols designed to probe potential willingness to use Urban Air Mobility and potential opposition from the non-user perspective in terms of noise, visual aesthetics, safety concerns, and other potential considerations. The study design sought the opinions of those who could be directly exposed to UAM as passengers as well as non-users on the ground exposed to the impacts of vertical take-off and land (VTOL) aircraft flying overhead in urban areas. Prior to commencing each focus group, participants were asked to complete a pre-focus group questionnaire to provide basic demographic and travel behavior information. A copy of the pre-focus group questionnaire and full protocol used for the focus groups can be found in Appendix 1 – Societal Barriers (General Population Survey). The focus group protocol followed the following structure:

- Pre-focus Group Questionnaire
- Familiarity with Air Taxi and Urban Air Mobility
- Thoughts and Impressions about Urban Air Mobility
- Automation and Electrification
- Ownership versus Sharing
- Security and Safety
- Privacy
- Concerns as a Non-User

8.2.2 Pre-Focus Group Questionnaire and Participant Demographics

The research team collected basic participant demographic data including: household income, highest level of educational attainment, age, race/ethnicity, and gender of focus group participants. In general, both focus groups had a small number of very low-income participants with household incomes of less than $15,000 per year and larger numbers of middle-to-upper income participants earning more than $75,000 per year. Both focus groups were skewed toward the upper middle-income demographic.

In terms of highest level of educational attainment, 60% of all focus group participants had a college degree (56% and 67% in Los Angeles and Washington, D.C., respectively). Among all focus group participants, there was an approximately equal distribution of participants with a high school diploma or vocational training and those with some post-graduate studies. Overall, focus group participation reflected a younger demographic. Forty-seven percent of all participants (56% and 33% in Los Angeles and Washington, D.C., respectively) were between 18 and 29 years old. The average age across all focus group participants was 36.2 (34.0 and 40.2 for Los Angeles and Washington, D.C., respectively).

A slightly larger percentage of participants were women (60%) than men (40%). While there was an approximate equal distribution of men and women in the Los Angeles focus group, the Washington, D.C. focus group was predominantly female with only one male participant. The race and ethnicity of focus group participants differed notably across both cities. In Los Angeles, 67% of the focus group participants were Caucasian compared to just 17% in Washington, D.C. In Washington, D.C., 50% of the focus group participants were African-American compared to none in Los Angeles. Detailed demographic information of all focus group participants can be found in Table 5 below.

Table 5: Focus Group Participant Demographics

	Focus Group Location		**Total**
HOUSEHOLD INCOME	*Los Angeles (n=9)*	*Washington, D.C. (n=6)*	*Both Locations (n=15)*
Less than $15,000	11%	33%	20%
$15,000 to $24,999	0%	0%	0%
$25,000 to $34,999	0%	0%	0%
$35,000 to $49,999	0%	0%	0%

$50,000 to $74,999	0%	33%	13%
$75,000 to $99,999	22%	17%	20%
$100,000 to $149,999	22%	17%	20%
$150,000 to $199,999	11%	0%	7%
$200,000 or more	11%	0%	7%
Decline to Answer	22%	0%	13%

HIGHEST LEVEL OF EDUCATIONAL ATTAINMENT

Less than high school	0%	0%	0%
High school/GED	0%	17%	7%
Vocational training	11%	0%	7%
Some college	11%	17%	13%
Associates degree	0%	0%	0%
Bachelor's degree	56%	67%	60%
Some graduate school	11%	0%	7%
Post-Graduate Degree	11%	0%	7%
Decline to Answer	0%	0%	0%

AGE

18-29	56%	33%	47%
30-39	11%	0%	7%
40-49	22%	17%	20%
50-59	0%	33%	13%
60-69	11%	0%	7%
70 years or older	0%	0%	0%
Decline to Answer	0%	17%	7%
Average Age	34.0	40.2	36.2

RACE/ETHNICITY

Caucasian	67%	17%	47%
African-American	0%	50%	20%
Hispanic/Latino	11%	0%	7%
Asian/Pacific Islander	11%	33%	20%
Other/Multi-Racial	11%	0%	7%
Decline to Answer	0%	0%	0%

GENDER

Male	56%	17%	40%
Female	44%	83%	60%
Decline to Answer	-	-	-

Note: Percentages may not add up to 100% due to rounding.

Prior to commencing each focus group, researchers administered a questionnaire to focus group participants to collect general travel behavior information, travel preferences, and attitudes and perceptions toward aviation and flying. The questionnaire first asked participants about their household size, the number of drivers, and the number of vehicles in their family. The average household size in the Los Angeles and Washington, D.C. focus groups were 3.2 and 3.5 persons, receptively. The average number of drivers per household in Los Angeles and Washington, D.C. was 2.8 in both focus groups. Vehicle ownership was slightly higher in Los Angeles with 1.8 vehicles per household compared to 1.7 in Washington, D.C. Household ownership was much higher among Southern California participants compared to Washington, D.C. Two-thirds of Los Angeles focus group participants owned their own home compared to all participants in Washington, D.C. who rent their home. One third of focus group participants in both locations had children living in their households.

Focus group participants were asked what factors they consider when picking a travel mode. Eighty-seven percent of participants (n=13 of 15) consider cost, and 80% (n=12 of 15) consider convenience as the top factors for selecting a transportation mode. Sixty percent of participants (n=9 of 15) consider travel time and 40% (n=6 of 15) consider amenities, such as the availability of radio or WiFi. Forty-seven percent (n=7 of 15) and 13% (n=2 of 15) considered environmental impact and safety, respectively. One person per focus group also considered the number of stops or transfers, as well as exercise, when selecting a transportation mode.

Focus group participants were also asked about their experiences flying including questions about:

- The types of aircraft or helicopters they have flown;
- How often they fly;
- The factors that discourage them from flying;
- Factors participants like and dislike about flying; and
- Factors that would cause them to consider flying more in the future.

Participants were asked, if they had ever flown in a large aircraft (41+ passengers), a small aircraft (1-40 passengers), or a helicopter. All participants (n=15 of 15) had flown in a large aircraft, and 87% (n=13 of 15) had flown in a small aircraft. Only 26% (n=4 of 15) had flown in a helicopter. The majority of participants fly at least once a year on average. Forty-seven percent (n=7 of 15) indicated flying an average of 1 to 6 times per a year, and 20% flew an average of 6 to 12 times per a year (n=3 of 12). One participant indicated that they flew at least monthly. Yet, despite a large number of frequently flyers, 27% (n=4 of 15) flew less than once a year, on average.

Cost was overwhelmingly cited as the top reason for not flying more often. Eighty percent of participants indicated that the cost of flying limited their frequency of air travel (n=12 of 15). Forty-seven percent also indicated that long lines discouraged participants from flying more frequently (n=7 of 15). Twenty-seven percent also indicated that inconvenience was a limiting factor to flying more often. In-flight entertainment, the on-board experience, and the ability to travel and get away were the factors participants liked about flying the most. Uncomfortable seats, vibrations, noise, and turbulence were cited as the greatest flying dislikes. Eighty-six percent of participants indicated that more affordable fares would entice them to travel more frequently (n=13 of 15). Sixty percent and 53% of all participants stated that easier access to the airport and shorter lines would also entice them to flying more frequently.

Finally, focus group participants were asked to share some basic information on their preferred travel mode for work travel, non-work travel, accessing a rail station, and accessing an airport. Walking and driving were each cited as the preferred travel mode overall by 60% of all participants. Public transportation (67%) and driving (78%) were cited as the most preferred travel modes in Washington, D.C. and Los Angeles, respectively, reflecting differences in the built environment and public transportation accessibility in each of these regions.

Overall, ridesourcing/transportation network companies (TNCs), such as Lyft and Uber, were cited as one of the preferred travel modes for non-work trips by 60% of participants across both focus groups (n=9 of 15). Driving and walking were also preferred modes by 47% of all participants (n=7 of 15). Taking ridesourcing/TNCs was cited as a preferred travel mode for accessing a rail station (53%, n=8 of 15) and airports

(60%, n=9 of 15), respectively. Carpooling to the airport was also a commonly preferred travel mode by 40% of participants (n=6 of 15).

8.2.3 Familiarity with Air Taxi and Urban Air Mobility

Focus group participants were asked if they were familiar with the term "air taxi." In Washington, D.C., 50% of participants (n=3 of 6) were familiar with the term. In Los Angeles, 44% of participants (4 of 9) had heard the term. Those that were familiar with the term compared it to an on-demand helicopter service, similar to New York City's BLADE, although no particular brands were mentioned. A few people who were unfamiliar with the term and learning about air taxi services for the first time compared it to a water taxi service. Many people who were new to the term immediately saw opportunities for short distance air travel that would be faster than existing ground transportation. A number of focus group participants were also confused by the term. These individuals were confused because they were not sure how far along the technology was in development and viewed "air taxis" and "flying cars" as a future concept from science fiction books and movies. In the Los Angeles focus group, one participant had heard the term Urban Air Mobility from a news story about Uber Elevate in the Los Angeles market.

8.2.4 Thoughts and Impressions about Urban Air Mobility

At this point in each of the focus groups, participants were presented with a video that explained the UAM concept along with a written description. The focus group moderator then answered clarifying participant questions about the concept before proceeding with the focus group protocol. Initially, participants asked for clarification on whether the aircraft take off and land similar to conventional airplanes and for additional information on how they fly, as well as on VTOL. Participants also wanted to know about how many people could be flown in the UAM aircraft, who pilots them or are they automated, how much noise they generate, and if they are safe. Other concerns raised included the type of training pilots receive and concerns about inclement weather. There were also questions about security and baggage handling. A few clarifying answers were provided. Many of these questions were explored in greater detail as the focus groups progressed.

After presenting the UAM concept to participants, the moderator then facilitated a discussion to gauge initial reactions to the concept, likes, and dislikes. Initial reactions to the concept included:

- Appreciation for not having to drive or sit in traffic;
- Convenience;
- Time savings and the ability to go farther distances faster than driving or public transportation;
- The ability to enjoy scenic views while flying; and
- The concept just "sounds cool."

However, not all initial reactions to the concept was positive. Common negative initial reactions included:

- The service looked expensive;
- Concern that the service will operate similar to a bus (with multiple take-off and landings for a single passenger trip);
- Impracticality for short distance travel;
- Inconvenient number of transfers as the concept assumes that you have to take a first-and-last mile connection using another travel mode to get to or from a vertiport;
- Demand would exceed available supply leading to high costs, long waits, or both;
- Limitations on landing locations;
- Low-level flight could be unsafe or visually undesirable;
- Greater safety risks associated with accidents than with ground transportation; and
- Potentially noisy in urban areas.

Fourteen out of 15 (93%) focus group participants stated that they were interested in using UAM, if it was safe. A few participants said they would only use the service, if it saved them time and money. A few participants also stated that they would not want to be early adopters of the technology and would want to be sure that the concept had been tested and proven safe. A few focus group participants also said they would use the service, not for time or monetary savings, but to select more attractive routing with scenic views (e.g., flying along the coast vs. driving on a more inland highway).

Participants were also asked how they would use UAM. In most cases, participants were interested in using it to replace longer vehicular trips in excess of one hour of driving time. These participants stated that they would prefer to use UAM to travel between short interregional destinations, such as Washington, D.C. to Baltimore and Los Angeles to San Diego. In general, there was a lot of support for the concept to replace existing short air trips because of the inconvenience of going to the airport. Some participants stated that they would use UAM to avoid vehicle congestion, however, only if time savings made up for the inconvenience of multi-modal transfers.

There was some disagreement among participants over whether they would use UAM for work or leisure trips. In general, most participants said that if the service were expensive, they would use it for periodic leisure trips and if it were affordable, they would use it for regular work trips. In general participants were hopeful that the cost would be low enough that they could replace existing public transit and Uber/Lyft trips with UAM. A few stated that if the service were expensive, they would treat themselves and use the service if they got a bonus or a good performance rating at work. There was a perception that this was a service for business executives, but participants were still interested in the service because of its convenience. A few expressed enthusiasm regarding the potential to work while flying on their work commute.

When asked about price, participants provided a variety of price comparisons. A number of people indicated that they would pay 10-20% more than an existing Lyft or Uber ride for the same trip. A number of people also said they were willing to pay a $1 to $2 per mile fee in any direction, or $25 to $40 per one-way trip, to go from the urban core to a suburb or edge city at the region's periphery. Only one participant in each focus group stated that she would not use UAM under any circumstances. She said that she wanted to use ground transportation for emergency access/egress.

8.2.5 Automation and Electrification

Next, participants were introduced to concepts about piloted, remote piloted, and automated aircraft. Participants raised a number of questions about pilot training and whether pilots would be held to the same standard of training as existing airline pilots. There was also some apprehension about piloted and automated UAM. Participants concerned with piloted concepts were concerned about road rage and potential aircraft misuse. Participants concerned with automated concepts expressed concern about safety, cybersecurity, and cyberterrorism.

Generally, participants overwhelmingly preferred piloted UAM. However, in both focus groups, a handful of participants were open to automated or remotely piloted UAM operations assuming that this would result in lower costs. In general, there was a strong sense that piloted and automated UAM aircraft should operate and co-exist in the same ecosystem, providing passengers the choice to select their preference and receive a discount, if they opted for a remotely piloted or automated service.

In general, participants preferred the idea of electric powered versus gasoline power aircraft. However, participants also expressed a strong preference for longer inter-regional trips that are currently only accessible with gasoline powered aircraft due to the present range limitations of eVTOL aircraft.

8.2.6 Ownership Versus Sharing

There was some interest among focus group participants in private fractional ownership of UAM aircraft among family members or sharing a privately-owned aircraft within a household. There was a general perception that if the aircraft were "affordable" (e.g., less than $100,000), it could be financed or leased, and it required less training than a traditional pilots license, then ownership would be preferable. A few people expressed concern about how to insure privately owned or fractionally owned aircraft.

There was also some interest among a handful of participants in owning and piloting eVTOL aircraft for-hire, similar to Lyft and Uber drivers driving paying passengers in their private vehicles. Interestingly, one

person did not want to own an eVTOL aircraft for personal use but only to offer for-hire flights for monetary compensation. Focus group participants also shared a number of concepts for how UAM could be shared. A few suggested that an aircraft could be shared by an apartment complex with a smaller scale landing pad for individual or a few aircraft.

In addition to sharing the aircraft (as an asset), participants were also asked about their willingness to share a flight with other passengers. In general, most participants were willing and assumed they would be sharing a flight with other passengers with some conditions. These included:

- A discount for sharing a flight with passengers they do not know (similar to Lyft Shared rides and uberPOOL);
- A rating process to rate how pleasant it is to fly with other passengers using the service; and
- A security screening process for all passengers.

8.2.7 Security and Safety

In both focus groups, the discussion about willingness to share a flight with other passengers that a traveler would not know in advance led to a lively discussion about safety and security. In general, focus group participants viewed UAM very differently from flying with unfamiliar passengers on board a commercial aircraft for a few key reasons including:

- Smaller aircraft and passengers are unable to get up, if they feel uncomfortable or relocate to another seat or section of the aircraft; and
- Fewer crew members makes passengers and aircrew more vulnerable to safety incidents.

In general, participants assumed that UAM would most likely be piloted. However, participants expressed concern that the aircraft could be hijacked due to its small size and perceived lack of a separation between the pilot and passengers. As such, many participants expressed a strong preference for a pilot compartment separate from the passenger compartment. Participants also expressed concern that passengers on board would cause harm to other passengers. Concerns about sexual assault were raised numerous times, particularly in an automated scenario without any flight crew on board. Interestingly, many focus group participants said they were unwilling to consider using any form of automated mobility (e.g., shared automated vehicles) for this very reason. As such, focus group participants expressed a strong preference for an “authority figure” on board, such as a flight attendant or other employee who could prevent and deter violence against passengers or intervene if an incident occurred on board. In the absence of a flight attendant or pilot on board, participants expressed a strong desire for an emergency button to abort the flight and land at the nearest vertiport, if they felt uncomfortable for any reason.

Most importantly, there was near unanimity that passengers should have to undergo some type of security screening before boarding. However, there was consensus that this screening process would have to be free of any lines (e.g., passengers just walk through a metal detector). Participants likened this screening process to walking through a metal detector at a museum or government building. There was unanimity that any security screening and boarding process should not take longer than 10 minutes from vertiport arrival to taking a seat in the aircraft, and the entire process had to be seamless all of the time. Specific to the airport shuttle market, focus group participants preferred having Transportation Security Administration (TSA) approved screening at the vertiport with an arrival on the airside of the airport terminal. There was also consensus that passengers should have to undergo prescreening to fly to ensure that unsafe or disrespectful passengers would not be permitted on board.

With respect to safety, all participants were willing to share their weight information for the purposes of safety and proper aircraft weight-and-balance. When asked about safety, participants held the aviation industry and the Federal Aviation Administration (FAA) with a high level of regard and trust. Participants generally assumed that if aircraft and pilots were FAA certified that UAM would be safe. There was, however, concern about sabotage or terrorism from outside the aircraft, such as “lasing” (using lasers to harm the pilot’s or passengers’ vision). Due to the low-level flight and the volume of planes, participants wanted safety equipment, such as anti-lasing glass and aircraft parachutes, in case of a mid-flight malfunction. Interestingly, participants also expressed a high dislike for pre-flight safety briefings. Given the potential frequency for UAM use, participants did not want to receive a pre-flight safety briefing every time they fly.

Instead, they preferred an online course or an annual or semi-annual course that one could take in person that certifies them to flying.

8.2.8 Privacy

In general, most passengers wanted to enjoy scenic and panoramic views while flying. However, there was some concern expressed about privacy, both from the perspective of passengers and non-users. For passengers, participants expressed concern that aircraft windows would make them feel "too exposed." There was concern that they would not feel secure or people on the ground would be able to see into the aircraft. As such, participants expressed a strong preference for aircraft tinting.

Additionally, participants expressed concern that people on the ground would have their privacy invaded due to urban aviation operations. There was a strong preference by participants to impose minimum flight altitudes that would limit visibility of individual people on the ground and prohibitions against flight over single-family residential neighborhoods. As such, many participants indicated that urban aviation should not necessarily be allowed to engage in direct point-to-point travel but should have to fly over existing highways and arterial roadways.

8.2.9 Concerns as a Non-User

In addition to privacy, there were some concerns raised from the perspective of the non-user. Primary concerns raised from the non-user perspective included: noise, followed by privacy, general safety, aesthetics, and pollution. In general, the technology was perceived to be safe, if pilots and aircraft received FAA certification and safety measures were incorporated into aircraft designs to safely abort flights in the event of an emergency. Of the concerns raised, the potential for noise was one of the most commonly raised concerns. However, participants were less concerned about individual aircraft noise and more concerned about total ambient aircraft noise from multiple aircraft operating in close proximity. Participants indicated a preference for limiting aircraft operations overnight, particularly in residential neighborhoods. In general, the concerns raised from the perspective of the non-user were lower than the potential concerns as a user. However, education, outreach, and proof of a safe UAM concept is key.

Key Findings (Focus Groups)	Key findings uncovered during the Los Angeles and Washington, D.C. focus groups include: • Perceptions that UAM is a premium service and a desire for the service to be offered at an affordable and accessible price point with only a minimal cost differential above ground transportation modes; • A strong preference for longer trips including intraregional trips in excess of a one-hour driving time in contrast to short interregional trips; • A strong preference for piloted, electric aircraft; • An expectation of cost savings and an on-board authority figure on board with remote piloted and automated aircraft concepts; • Willingness to share flights with other passengers and to share ownership of the aircraft, which suggests the need for more research into peer-to-peer business models; • The need for an expedited passenger screening process for boarding passengers; • Potential privacy concerns for both users and non-users; and • General concerns about aggregate noise from multiple aircraft operating in close proximity and safety concerns associated with on board passengers and external sabotage.

8.3 General Population Survey

8.3.1 Methodology

In August 2018, we conducted an exploratory survey of approximately 1,700 respondents in five U.S. cities. We created the general population survey and distributed it to a survey panel using the online survey platform Qualtrics, and survey participants were compensated after completion. Potential survey participants were screened based on their gender to obtain a more uniform distribution of male and female respondents. The survey participants were also screened based on the metropolitan region in which they resided. The completed survey target included approximately 350 respondents each from Houston, Los Angeles, New York, the San Francisco Bay Area, and Washington, D.C. For each region, we aimed to collect responses that were a fair approximation of the demographic distribution of the general population of each of the metropolitan areas in the study. The metropolitan regions were selected to capture variability in demography, geography, weather patterns, traffic characteristics, and the built environment (e.g., density, walkability, public transit accessibility), as well as the presence of past or present air taxi services. Each of the cities also has unique features that potentially make them more receptive or resistant to UAM technology, detailed in Table 6.

Table 6: Five U.S. Metropolitan Regions Surveyed

Metropolitan Region	Features	Weather	Existing UAM Services
Houston	- Large number of helipads – Infrastructure for UAM present - Long history of helicopter services serving offshore drilling operations	- Humid subtropical - Very hot and humid summer, mild and temperate winter - Annual precipitation: 50 inches	x
Los Angeles	- High-traffic, with long distance and high commute times - High level of public knowledge about UAM due to Uber Elevate (based on focus group results)	- Mediterranean climate; dry summer and a winter rainy season - Microclimates – daytime temperatures can vary as much as 36°F - Annual precipitation: 14.93 inches	SkyRyde (fixed wing aircraft)
New York City	- Long history of helicopter services - Several high-profile aviation incidents since 2001 including 9/11 (AA #11 & UA #175), AA #587, US #1549, and 2018 Eurocopter AS350 crash - Existing app-based on-demand helicopter service (BLADE)	- Humid subtropical - Cold, damp winters - Mild spring and autumn - Hot and humid summers - Annual precipitation: 50 inches	BLADE (helicopters and fixed wing aircraft)
San Francisco Bay Area	- Perceived as a tech/early adopter market - Potential for notable societal barriers from local environmentalists including noise, aesthetics, etc.	- Warm-summer Mediterranean climate - Mild climate with little seasonal variation - Microclimates	x

		- Annual Precipitation: 24 inches	
Washington, D.C.	- Perhaps different perceptions on security - N. VA (as an edge city) has a lot of similar built environments to other edge cities	- Humid subtropical - Chilly winters with light snow and hot, humid summers - Annual Precipitation: 40 inches	x

The survey evaluated public perceptions and potential societal barriers of UAM. In the survey, we first probed respondents' familiarity with the UAM concept and then introduced the technology through technical descriptions and a brief video describing the concept. Throughout the survey, we asked respondents questions that probed their perceptions and reactions to travel scenarios in UAM aircraft. Due to the novelty of the technology, we supplemented each of the UAM travel scenarios and any new concepts with infographics and short descriptions. Examples of topics explored in the survey included whether: 1) respondents would prefer automated, remote piloted, or piloted UAM; 2) the presence of other passengers or a flight attendant on board impacted their willingness to use the service; and 3) respondents would prefer for-hire services or to own their own UAM aircraft. The survey also sought to identify concerns from a non-user perspective such as noise or safety concerns (from the perspective of a person on the ground).

Table 7: Willingness-to-Fly Scale

Original Willingness-to-fly Scale from Rice, Mehta, et al., 2015	Adapted Willingness-to-fly Scale
I would be willing to fly in this situation.	If I were to fly in an Urban Air Mobility aircraft, I would feel willing.
I would be comfortable flying in this situation.	If I were to fly in an Urban Air Mobility aircraft, I would feel comfortable.
I would have no problem flying in this situation.	If I were to fly in an Urban Air Mobility aircraft, I would feel concerned.
I would be happy to fly in this situation.	If I were to fly in an Urban Air Mobility aircraft, I would feel satisfied.
I would feel safe flying in this situation.	If I were to fly in an Urban Air Mobility aircraft, I would feel safe (i.e., protected against mishaps and accidents)
	If I were to fly in an Urban Air Mobility aircraft, I would feel secure (i.e., protected against deliberate and intentional threats)
I have no fear of flying in this situation.	If I were to fly in an Urban Air Mobility aircraft, I would feel afraid.
I feel confident flying in this situation.	If I were to fly in an Urban Air Mobility aircraft, I would feel confident.

Following feedback from the focus groups, the survey draft was refined to incorporate questions related to noise concerns and willingness to pilot a UAM aircraft. We also incorporated the "willingness to fly" scale, originally developed by Rice, Mehta, et al. (2015) to measure differences in passenger perceptions. The scale consists of seven statements to be rated using a 5-point Likert scale ranging from -2 (strongly disagree) to 2 (strongly agree) with a neutral option (0). The original seven statements of the scale were adapted for use in this survey to capture the respondents' perceptions of UAM, as well as to compare perceptions

of flying in piloted, remotely piloted, or automated UAM and flights in differing weather conditions. The language: "I would have no problem flying in this situation" was replaced with language regarding whether the participant would feel concern. For example, we replaced "I would be happy to fly in this situation" with "I would feel satisfied." The adapted scale in our survey also distinguishes between "safety" and "security." Safety is defined as protected against mishaps and accidents, while security is defined as protected against intentional threats. The revised statements can be compared in Table 7 above.

In August 2018, we administered a general population survey using Qualtrics, an online survey platform. The survey design addressed the following topics: 1) respondent demographics, 2) recent travel behavior, 3) typical commute behavior, 4) familiarity with aviation, 5) existing aviation experience and preferences, 6) familiarity with UAM, perceptions about UAM, 7) perceptions toward technology and UAM, 8) stated preference and willingness to pay, 9) weather considerations, 10) market preferences, and 11) perceptions from the non-user perspective.

This section includes an abbreviated summary of survey findings excluding analyses of respondent travel behavior, existing aviation experience, the use of SAVs and AVs in a driverless vehicle future, and weather considerations. The complete analysis including these omitted sections is included in Appendix 1 – Societal Barriers (General Population Survey). Where appropriate, we have also noted the page number of the appendix where figures and tables not critical to the abbreviated text may be found.

Methodological Limitations: Survey-based research is a useful technique for gathering a wide range of data about a population such as the attitudes, behavior, and characteristics of the survey population. Surveys are relatively easy to administer and offer flexibility in data collection. However, limitations exist with this methodological approach. For example, responses to survey questions are self-reported and are subject to respondent bias. It is also possible that a survey questionnaire may not evoke truthful responses from the sample population (Ponto, 2015). Another possible source of error could occur due to priming and survey questions must be carefully ordered and worded to prevent influencing how people respond to subsequent questions. Finally, it is challenging for individuals to respond to an innovation without having direct experience with it. This impacts a respondent's ability to answer questions based upon limited to no experiential understanding. Our survey results likely reflect this limitation. In the future, we recommend conducting a survey with early adopters or using a flying simulator, for instance.

8.3.2 Respondent Demographics

Our survey collected basic demographic information of respondents including: household income, education, age, race/ethnicity, gender, and type of housing. Table 8 below provides a summary of each of these demographic categories across all respondents as well as disaggregated per city. Table 8 also provides the 2016 American Community Survey (ACS) data as a reference point for the demographic distribution of each city.

In general, the respondents represented the distribution of household income levels across the cities, with slight underrepresentation of the highest income brackets (respondents with more than $150,000 in household income). Across the cities, the respondents of the San Francisco Bay Area and New York tended to fall into higher income brackets. In terms of educational attainment, the respondents were skewed towards those who had attained a bachelor's or graduate degree (36% with a bachelor's degree and 32% with a graduate degree or currently in graduate school). Only 1% of the respondent population had less than a high school degree, while the average across the cities in the 2016 ACS survey was closer to 16%.

Overall, the respondent population reflected the 2016 ACS age distribution. The distribution is slightly biased toward a younger demographic (those 25 to 34 years of age), but there is also a slight overrepresentation of respondents in the 65 to 74 age group (17% in the survey population vs 7% in the general population). Los Angeles was skewed more heavily towards a younger population, where 44% of the respondents were between 18 to 34 years of age. With respect to race and ethnicity, approximately 55% of respondents were White/Caucasian. Hispanics or Latinos were underrepresented by the survey population at approximately 10% of respondents. In Houston and Los Angeles, this underrepresentation was a bit more prominent. For example, Los Angeles has a population that is 45% Hispanic or Latino, but only 15% of survey respondents were Hispanic or Latino. Across the entire sample of survey respondents, a slightly larger percentage of women (57%) participated in the survey than men (43%). For housing, respondents in New York tended to live in the highest density housing, with 77% living in buildings with more than 10 units.

Respondents in Houston lived in the lowest density housing, with 61% living in detached single-family homes.

Table 8: Demographic Data

	Total		Houston		San Francisco Bay Area		Los Angeles		Washington, D.C.		New York City	
HOUSEHOLD INCOME	**2016 ACS**	**Survey**	**2016 ACS**	**Survey**	**2016 ACS**	**Survey**	**2016 ACS**	**Survey**	**2016 ACS**	**Survey**	**2016 ACS**	**Survey**
Less than $10,000	6%	5%	6%	6%	6%	3%	7%	4%	5%	8%	4%	6%
$10,000 - $14,999	4%	4%	4%	5%	5%	3%	5%	5%	4%	4%	2%	2%
$15,000 - $24,999	8%	8%	10%	6%	9%	7%	9%	9%	7%	10%	5%	6%
$25,000 - $49,999	18%	16%	22%	20%	21%	13%	18%	16%	15%	18%	14%	13%
$50,000 - $74,999	16%	16%	17%	22%	16%	14%	15%	14%	14%	13%	15%	17%
$75,000 - $99,999	12%	14%	12%	14%	12%	14%	12%	18%	12%	13%	13%	12%
$100,000 - $149,999	16%	13%	15%	12%	15%	14%	16%	15%	18%	12%	20%	14%
$150,000 - $199,999	8%	7%	7%	4%	7%	9%	8%	8%	10%	6%	12%	8%
$200,000 or more	11%	9%	8%	5%	9%	13%	11%	5%	16%	8%	15%	11%
EDUCATION	**2016 ACS**	**Survey**	**2016 ACS**	**Survey**	**2016 ACS**	**Survey**	**2016 ACS**	**Survey**	**2016 ACS**	**Survey**	**2016 ACS**	**Survey**
Less than high school/Currently in High School	16%	1%	18%	2%	12%	1%	21%	1%	10%	0%	14%	1%
High school graduate (includes equivalency)	22%	13%	23%	19%	16%	8%	20%	11%	19%	18%	25%	8%
Some college, no degree/Currently in College	18%	5%	21%	6%	19%	4%	20%	7%	17%	6%	16%	2%
Associate's degree	7%	10%	7%	12%	7%	10%	7%	11%	6%	8%	7%	9%
Bachelor's degree	23%	36%	20%	34%	28%	44%	21%	37%	25%	28%	22%	37%
Graduate or professional degree/Currently in post-graduate degree	15%	32%	11%	26%	19%	31%	11%	30%	24%	36%	16%	39%
AGE	**2016 ACS**	**Survey**	**2016 ACS**	**Survey**	**2016 ACS**	**Survey**	**2016 ACS**	**Survey**	**2016 ACS**	**Survey**	**2016 ACS**	**Survey**
18 - 24 years	9%	9%	10%	11%	8%	7%	10%	10%	9%	13%	9%	7%
25 - 34 years	15%	26%	15%	26%	16%	18%	15%	34%	15%	25%	15%	23%
35 - 44 years	14%	18%	14%	13%	15%	18%	14%	17%	15%	19%	13%	17%
45 - 54 years	14%	13%	13%	10%	14%	16%	14%	9%	15%	13%	14%	13%
55 - 64 years	12%	16%	11%	16%	13%	20%	11%	10%	12%	15%	12%	17%
65 - 74 years	7%	17%	6%	18%	8%	18%	7%	15%	7%	12%	8%	17%
75+ years	6%	5%	4%	5%	6%	4%	6%	4%	5%	3%	6%	6%
RACE	**2016 ACS**	**Survey**	**2016 ACS**	**Survey**	**2016 ACS**	**Survey**	**2016 ACS**	**Survey**	**2016 ACS**	**Survey**	**2016 ACS**	**Survey**
Hispanic or Latino	30%	10%	36%	12%	22%	6%	45%	15%	15%	4%	24%	12%
White alone	41%	55%	38%	54%	41%	51%	30%	53%	47%	54%	48%	65%
Black or African American	14%	16%	17%	20%	7%	3%	6%	16%	25%	31%	16%	8%
American Indian or Alaska Native alone	0%	1%	0%	0%	0%	1%	0%	1%	0%	1%	0%	1%
Asian alone	13%	12%	7%	9%	25%	29%	15%	10%	10%	4%	11%	10%
Native Hawaiian or Pacific Islander alone	0%	0%	0%	0%	1%	1%	0%	0%	0%	0%	0%	0%
Other alone	0%	2%	0%	3%	0%	2%	0%	2%	0%	2%	1%	1%
Two or more races	2%	2%	2%	1%	4%	4%	2%	1%	3%	3%	2%	2%
GENDER	**2016 ACS**	**Survey**	**2016 ACS**	**Survey**	**2016 ACS**	**Survey**	**2016 ACS**	**Survey**	**2016 ACS**	**Survey**	**2016 ACS**	**Survey**
Female	51%	57%	50%	63%	51%	50%	51%	59%	51%	56%	52%	57%
Male	49%	43%	50%	37%	49%	50%	49%	41%	49%	44%	48%	43%
HOUSING TYPE	**2016 ACS**	**Survey**	**2016 ACS**	**Survey**	**2016 ACS**	**Survey**	**2016 ACS**	**Survey**	**2016 ACS**	**Survey**	**2016 ACS**	**Survey**
Detached single-family ho	46%	43%	63%	61%	50%	48%	37%	50%	50%	42%	46%	13%
Building/house with fewer than 10 units	26%	19%	12%	12%	24%	26%	31%	22%	27%	24%	28%	9%
Building with between 10 and 100 units	27%	23%	21%	13%	25%	20%	32%	22%	22%	21%	25%	41%
Building with more than 100 units		14%		12%		5%		5%		12%		36%
Mobile home/RV/Trailer	1%	1%	5%	1%	2%	1%	1%	0%	1%	1%	1%	1%

8.3.3 Familiarity with UAM

At the start of the survey, respondents were asked whether they were familiar with the concept of UAM. This question was asked before the survey and respondents were provided with a brief video and written description introducing the UAM concept. Only 23% of the respondents were familiar with the concept of UAM. Analyzing familiarity with UAM by demographic categories, we found that familiarity was slightly higher in Los Angeles (32%) than the other cities, possibly due to Uber Elevate announcing Los Angeles as one of the two first launch cities with plans to commence commercial operations in the region as soon as 2023. Men tended to be more familiar with UAM than women, at 30% and 19%, respectively. Age appeared to be correlated with familiarity with the concept, with Millennials and Gen Xers reporting higher levels of familiarity (Figure 21).

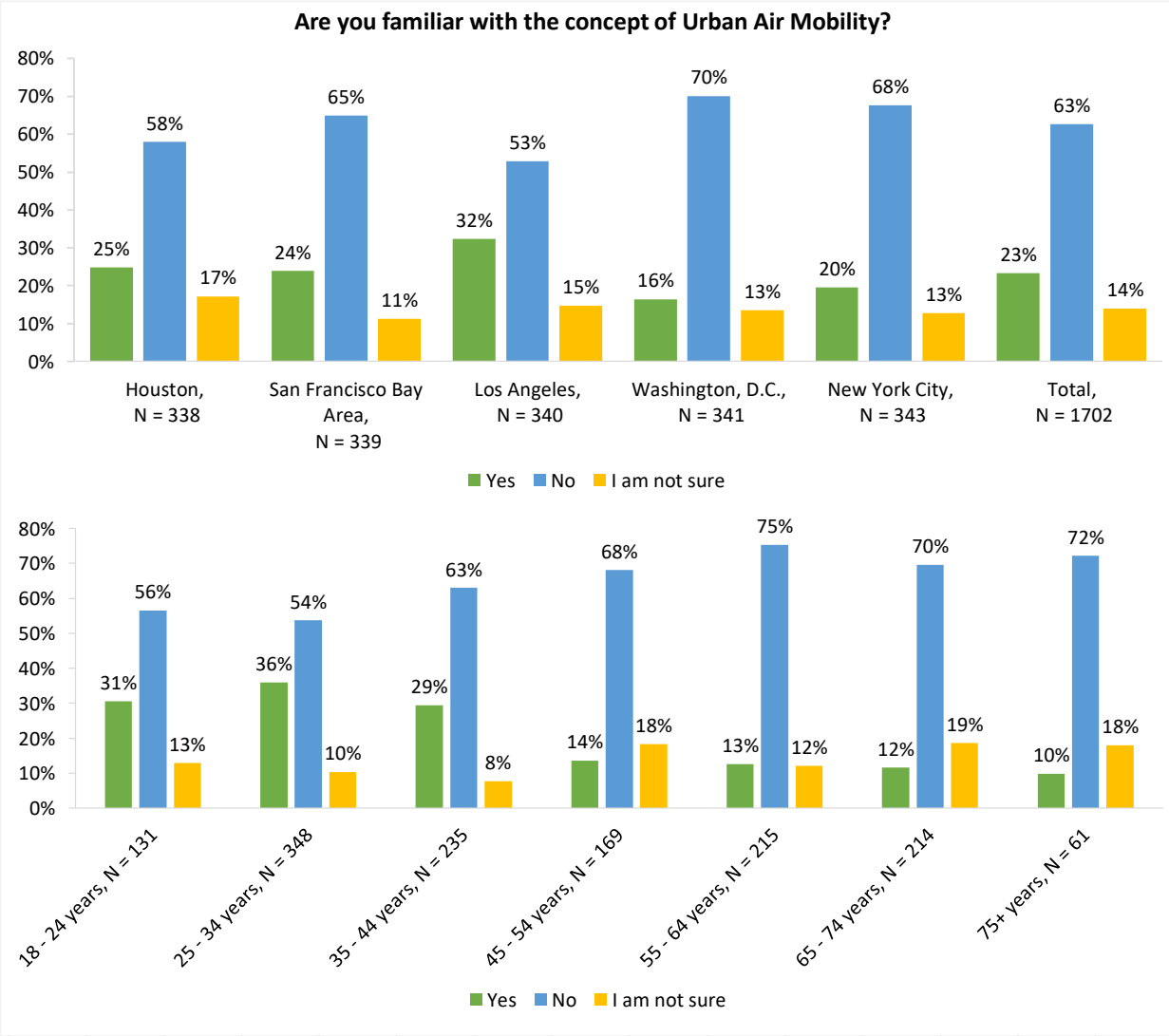


Figure 21: Survey responses to UAM familiarity

8.3.4 Travel Behavior

One of the objectives of this research project was to explore potential markets and future use cases for UAM. Examples of future use cases include: 1) air taxis, a service primarily used to access airports or 2) emergency travel, such as air ambulances. To inform this market analysis, respondents were asked a series of questions regarding their most recent non-commute trip. By targeting the most recent non-commute trip, the survey aimed to capture a glimpse into the travel behavior of the populations of each of the five U.S.

cities. Respondents were asked the purpose of their most recent trip, the modes used to travel to the destination, and the distance traveled of the trip. For detailed information on the existing travel behavior of survey respondents, please see Appendix 1 – Societal Barriers (General Population Survey).

8.3.5 Familiarity with Aviation and Existing Preferences

We wanted to measure the respondents' comfort with using air travel and identify any barriers to UAM based on previous aviation experience. To gauge the respondent's familiarity with aviation, respondents were first asked to identify if they had flown on four types of aircraft: 1) a large airplane (81+ passengers), 2) a regional airplane (41-80 respondents), 3) a small airplane (1-40 passengers), and 4) a helicopter. For each aircraft, respondents were shown a representative image of the aircraft type. According to a study by Airlines for America (Heimlich & Jackson, 2017), 89% of Americans have traveled by airline at some point in their lifetime. Similarly, 87% of the respondents had flown in large airplanes and 74% had flown in regional airplanes at least once. The respondent population was familiar with flight, but a smaller proportion of the population had flown in small aircraft. Approximately half of the respondents had flown in small airplanes (1-40 passengers), and 29% had flown in a helicopter. For more information on the existing aviation preferences of survey respondents, please see Appendix 1 – Societal Barriers (General Population Survey).

8.3.6 UAM Perceptions

As mentioned previously, the survey respondents were introduced to the concept of UAM through a short video clip and description of the technology. The video clip was approximately a minute and a half long, and it consisted of Uber Elevate's promotional introduction to their future urban air ridesourcing product, Uber Air. In the promotional video, viewers follow the steps of an individual taking a piloted UAM trip for their commute home. For the survey introduction to UAM, we edited the video clip to remove Uber logos, and the final 12 seconds of the video were removed to eliminate references to Uber Air. The following definition prefaced the video in our survey:

"Urban Air Mobility (UAM) is a safe and efficient system for air passenger transportation within an urban area. UAM supports a mix of onboard/ground-piloted and increasingly automated operations."

After the introduction of UAM, we asked the respondents to select from a series of emotional states that matched their initial reaction. Overall, UAM invoked a positive to neutral response, with some skepticism. The initial feelings were consistent across all cities; however, variation existed across other demographic categories. For initial reactions, 36% of male respondents selected "Excited" compared to 26% of female respondents. Excitement for the concept tended to be correlated with household income, perhaps due to perceived service cost. This corresponds with the written responses of several participants who expressed concerns that UAM would be a mode used predominantly by higher income travelers. Younger respondents tended to be more excited about the concept, while skepticism tended to increase with age. Table 19 in Appendix 1 – Societal Barriers (General Population Survey) presents the initial reactions of the respondents, disaggregated by demographic categories.

Next, we introduced respondents to the willingness-to-fly scale, which was presented in Table 7 above. Respondents were asked to rate on a 5-point Likert scale eight statements intended to capture their UAM travel perceptions. Respondents were cautiously optimistic about the idea of flying in a UAM aircraft. Of the aggregated respondents, 55% were willing to fly in a UAM aircraft, and 50% assumed they would be comfortable in a UAM aircraft. However, only approximately 36 to 37% believed they would feel safe and secure flying in a UAM aircraft. For each statement regarding UAM aircraft feelings (willingness, safety, fear, concern), approximately one a third of the respondents were neutral. This neutrality might be influenced by the lack of personal experience with this technology; some of the respondents might have difficulty imagining their reaction. A follow-up study could capture more reactions to UAM flight simulators or actual flights. Men were more slightly more comfortable and willing to use UAM than women, and willingness to use UAM was highest among Millennials. We found that the percentage of objections to flying in a UAM aircraft rises as age increases (Figure 22).

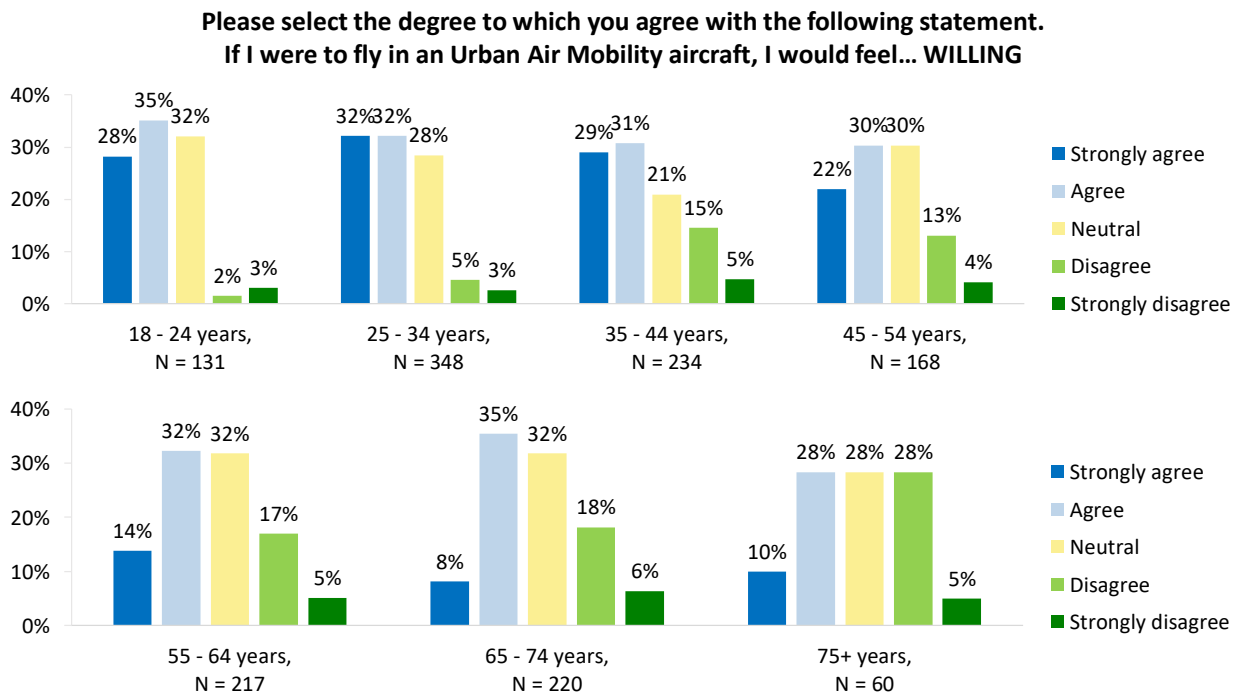


Figure 22: Willingness to fly among age groups

Ordinal Logistic Regression: We performed an ordinal logistic regression to evaluate the impact of socio-economics and congestion on willingness to use UAM. In the ordinal logistic regression model, the dependent variable is an ordinal. Examples of ordinal variables include items on a Likert scale. For our study, respondents chose one of five ordered responses for their willingness to use UAM: "Strongly agree," "Agree," "Neutral," "Disagree," and "Strongly disagree." The socio-demographic variables considered included age, education, household income, race/ethnicity, and gender. The respondents' commute distance in miles was used as a stand-in variable for congestion. Finally, familiarity with the UAM concept was included as an independent variable. Before building the ordinal regression model, crosstabs were performed on each of the socio-economic variables to identify overarching trends and important variables for regression analysis. From the crosstabs presented in Table 20 in Appendix 1 – Societal Barriers (General Population Survey), the survey team expected that age, gender, and income will be significant variables in the ordinal logistic regression model.

Model estimation was completed using the **ordinal** package in R. The ordinal regression model is displayed in Table 21 in Appendix 1 – Societal Barriers (General Population Survey). Positive coefficients indicate that the variable increases willingness to fly. The variables for age, gender, and familiarity with the UAM concept before the survey are the most significant variables. The coefficient for age was negative, indicating that older respondents were less willing to fly. The coefficients for male gender and "yes" for familiarity were positive. Commute distance and Hispanic or Latino ethnicity were significant, but less influential. Both had positive coefficients, indicating that respondents with longer commutes and Hispanic/Latino respondents tended to be willing to fly in UAM aircraft.

8.3.7 Perceptions Toward Technology and UAM

Through a series of scenarios with varying degrees of automation, we also explored the public's perceptions towards the level of automation of UAM aircraft. We presented five scenarios to the respondent: flying in (1) an automated aircraft, (2) a remotely piloted aircraft with a flight attendant on board, (3) a remotely piloted aircraft without a flight attendant on board, (4) an automated aircraft with a flight attendant on board, and (5) an automated aircraft without a flight attendant on board. As noted in the methodology, we showed

respondents infographics representing each of the three levels of automation (automated, remotely piloted, and piloted) to help the respondents visualize the scenarios. For each of these scenarios, the respondents were asked if they would be willing to fly alone, with other passengers that they knew, and with passengers they did not know.

Of the respondents who were willing to fly in a UAM aircraft, the respondents preferred to travel with other passengers that they knew (Figure 23). However, respondents were more willing to fly alone or with strangers in a piloted aircraft. The presence of a flight attendant only very slightly increased willingness to fly in remotely piloted or automated aircraft. We also explored the respondents' perceptions of comfort (Figure 23) and safety and security (Figure 24). For this study, we defined safety as "protected against mishaps and accidents," and security is defined as "protected against deliberate and intentional threats." The respondents' answers were closely correlated to their willingness to fly – respondents felt more safe, secure, and comfortable in piloted aircraft than in remotely piloted or automated aircraft. As displayed in Figure 23 and Figure 24, the presence of a flight attendant had a slight effect on respondents' feelings toward travel in a remotely piloted or automated aircraft; approximately 5 to 10% more respondents felt comfortable, safe, and secure traveling in a UAM aircraft if a flight attendant was on board. However, these results may be affected by lack of experience with UAM or survey fatigue. It is possible that survey respondents would have had difficulty visualizing the different levels of automation and gauging their feelings toward UAM flight.

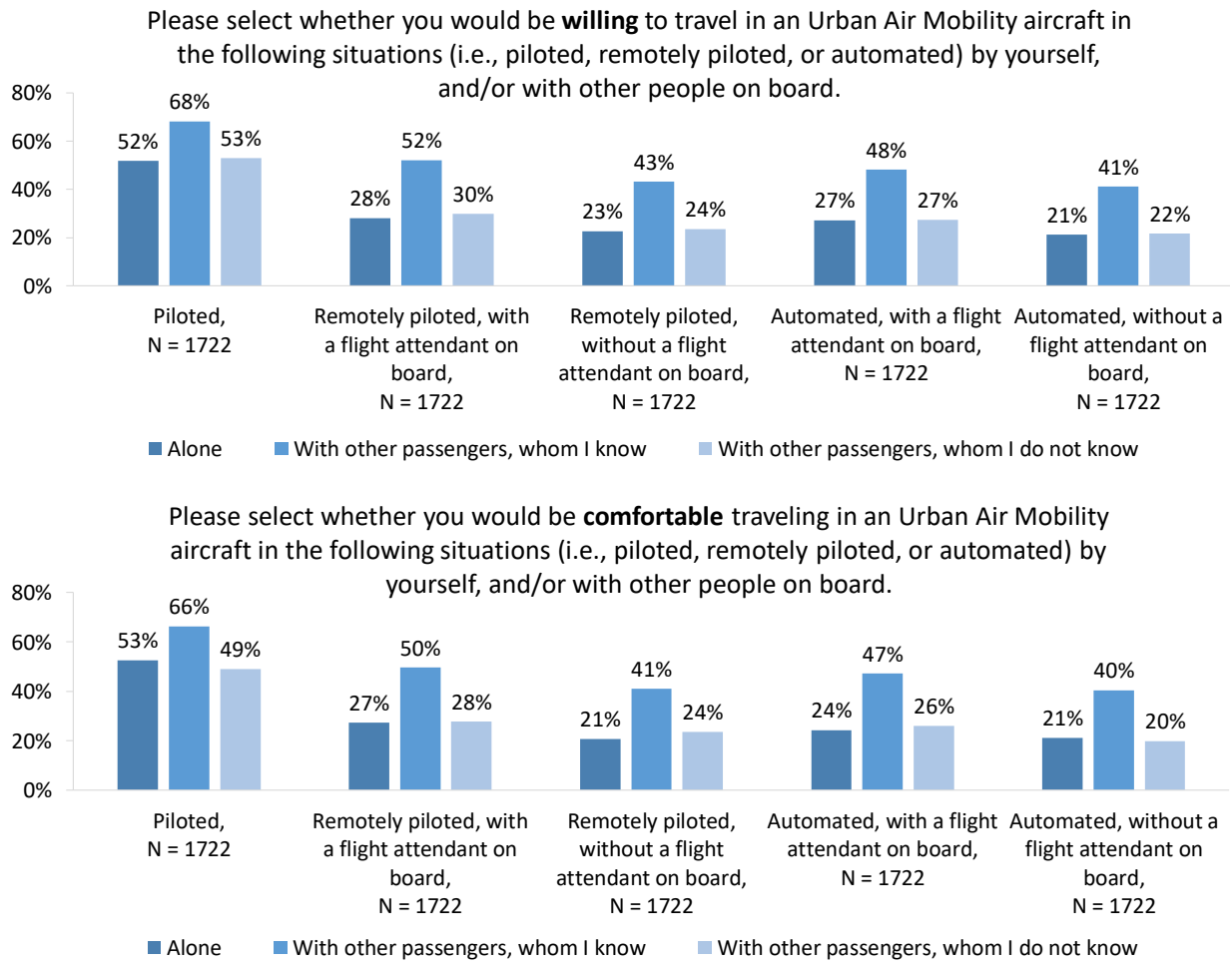


Figure 23: Perceptions of willingness and comfort

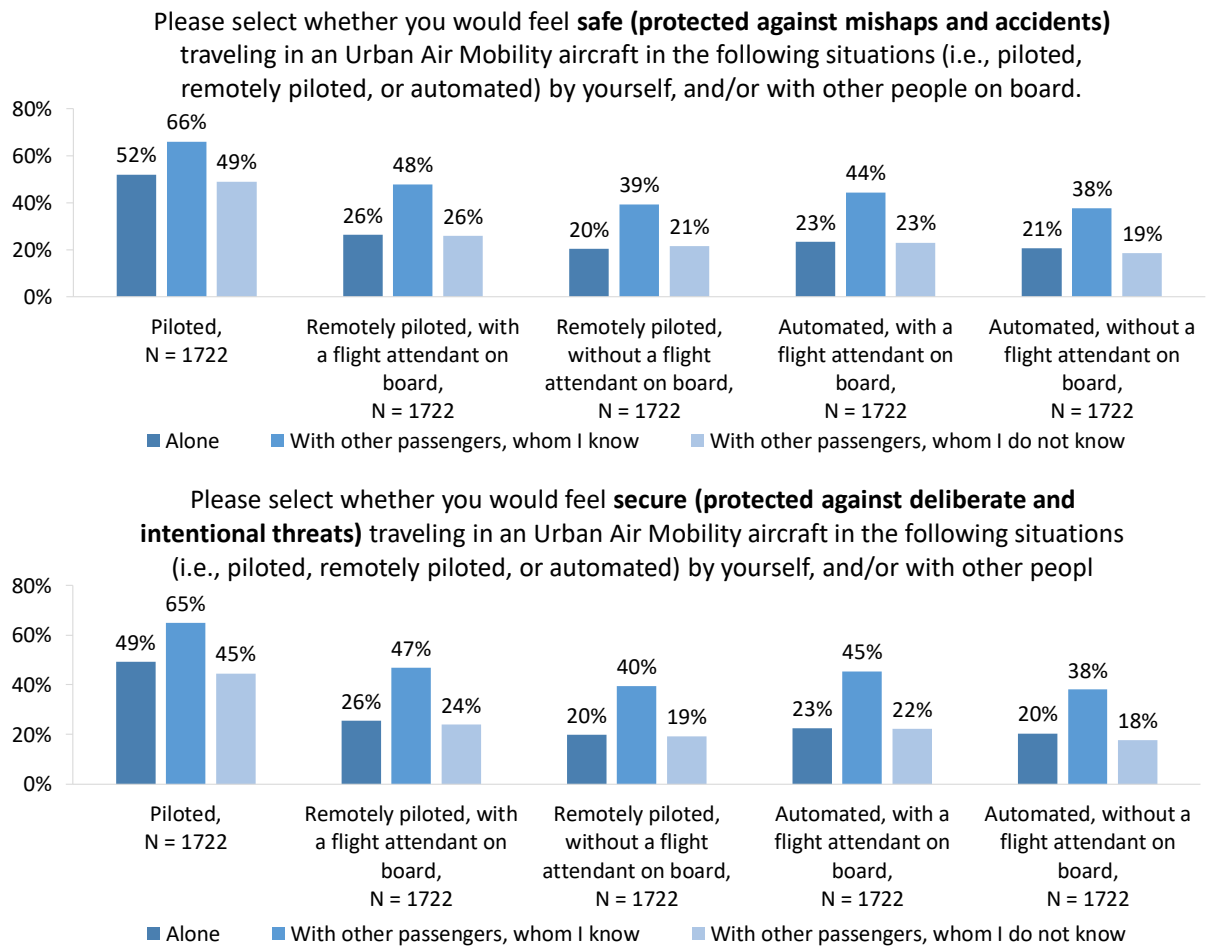


Figure 24: Perceptions of safety and security

8.3.8 Stated Preference & Willingness to Pay

The survey also contained a block of stated preference (SP) questions meant to capture participants' preferences for UAM travel. The respondents were presented five hypothetical trips, each varying randomly in three attributes: trip purpose, trip cost, and distance traveled. The levels of each attribute are shown in Table 9. The respondents were presented one trip at a time and asked to choose whether they would consider taking the trip – a dichotomous outcome of either "Yes, I would take this trip" or "No, I would not take this trip."

Table 9: Stated Preference Attributes

Attribute	Level
Trip Purpose	Going to Airport, Going to Work/School, Recreational (excludes work trips)
Cost (One-Way)	$12, $26, $48, $72, $93, $145
Distance (Miles)	5, 12, 23, 36, 46, 60

Before the five hypothetical scenarios, the respondents were presented a practice scenario to set a reference point for UAM travel cost for the set of SP questions. The practice scenario was identical for all respondents, with trip purpose set to "Going to Work/School", cost set to $50, and distance set to 10 miles. The pricing was set to $5 per mile based on an estimate from Uber Air. Uber estimates that their on-demand electric Vertical Take-off and Landing (eVOTL) taxis will initially cost $5.73 per passenger mile (Dickey, 2018).

The outcome data from the SP questions were used to build a logistic regression model with the binary outcome ("yes" or "no" to taking the trip) as the dependent variable, and the trip attributes and respondent characteristics as the predictor variables. The logistic regression model was created in R using the **glm** function. Model results are shown in the extended survey summary in Table 22 of Appendix 1 – Societal Barriers (General Population Survey).

Each of the attributes of the stated preference scenarios – trip purpose, cost, and distance – were statistically significant predictors for the decision to take a UAM trip. For every one mile increase in trip distance, the logarithm of the odds of the respondent taking the trip increases by 0.018. For every one dollar increase in trip cost, the logarithm of the odds of the respondent taking the trip decreases by 0.0213. If the purpose of the trip is going to work or school, versus going to the airport, the logarithm of the odds of taking the trip decrease by 0.715. If the purpose of the trip is recreational, as opposed to going to the airport, the logarithm of the odds of taking the trip decrease by 0.141. These results indicate that UAM travel would be more successful for trips that are longer, and respondents were not as interested in using UAM aircraft for commuting as they were for recreational trips or trips to the airport.

Similar to the results of the ordinal logistic regression model, age, gender, and familiarity with the concept of UAM were statistically significant predictors of whether a person would take a UAM trip. Younger respondents, male respondents, and respondents familiar with UAM prior to the survey were more likely to take a UAM trip. The coefficient for income was statistically significant and positive, indicating respondents with higher income were more likely to take UAM trips. Survey respondents from Los Angeles were more likely to agree to take a trip compared to respondents from Houston, and respondents from the San Francisco Bay Area were less likely to agree to take a UAM trip compared to respondents from Houston.

In order to measure how well the logistic regression model fits, the research team tested whether the model with predictors fits significantly better than a null model using a likelihood ratio test. The test statistic used is the difference in residual deviance between our model and a null model. We obtained a chi-square of 2544 with 30 degrees of freedom and an associated p-value of 0, indicating that the estimated model fits significantly better than a null model. The log-likelihood of our model was -5290.

The null deviance of the model is 13123 on 10201 degrees of freedom. The residual deviance is 10579 n 10171 degrees of freedom. The AIC is 10641, and the number of Fisher Scoring iterations is 4.

The research team also estimated the willingness-to-pay for distance traveled. The ratio of coefficients ($\beta_{trip_distance}/\beta_{trip_cost}$) represents the survey respondent's willingness to pay for additional miles traveled. In our model, $\beta_{trip_distance}$ is estimated to be .018 and β_{trip_cost} is estimated to be -0.0213, implying that the respondents were willing to pay approximately 0.85 dollars more for a trip whose distance is one mile longer.

8.3.9 Weather Considerations

Naturally, weather conditions impacted the willingness of a respondent to fly in a UAM aircraft. While a significant portion of the respondents (more than 50% in each of the weather scenarios, and as high as 81% for hot and cold conditions) were willing to fly in a UAM aircraft under adverse weather conditions, respondents reported increased levels of fear and concern. The survey respondents were apprehensive towards flying in rain, snow, low visibility, and turbulence, while they tended to be indifferent to hot and cold weather conditions. Respondents were the most afraid of snow (54%), fog/low visibility (57%), and turbulence (54%). For more information on how weather scenarios impacted survey respondents' perceptions of UAM, please see Appendix 13.1.5.

8.3.10 Market Preferences

In addition to public concerns and perceptions of UAM technologies and operations, we also probed market preferences. The survey questions explored the circumstances under which the public saw itself using

UAM, how much they were willing to pay for the service, and perceptions toward ownership and vertiport usage. First, to investigate the consumer's preferences for UAM flight, we asked respondents a question designed to capture the tradeoff between cost and privacy. Respondents were asked whether they would be willing to pay a premium fare to fly alone, without any other passengers. Across the survey sample, 14% of the respondents were willing to pay a premium fare, and approximately 33% were willing to consider a premium fare depending on the trip. Notably, 21% of the respondents were unwilling to pay the premium because they did not want to fly alone. For these passengers, other incentives could be considered when designing UAM experiences that charge premium fares. Comparing among the cities, respondents from Los Angeles valued their privacy most highly, with 22% willing to pay a premium fare to fly alone (Figure 25).

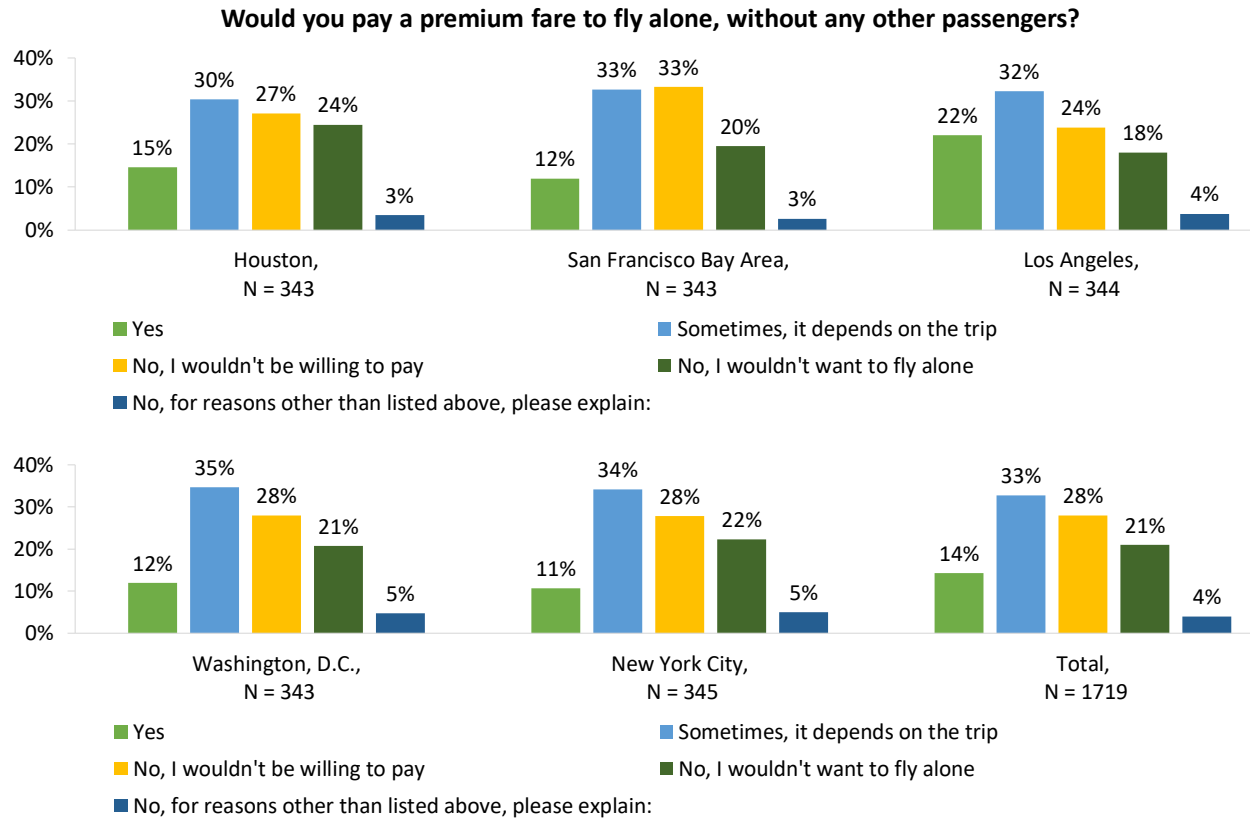


Figure 25: Willingness to pay a premium fare to fly alone

Overall, men were more willing to pay a premium fare to fly alone without any other passengers – the largest discrepancy between willingness to pay a premium to fly alone was due to reluctance among women to fly alone (27% of women were unwilling to fly vs. 13% among men). Household income did not appear to impact a person's willingness to fly alone, but age had a significant impact. Older respondents were much less likely to pay a premium fare to fly alone (Figure 26).

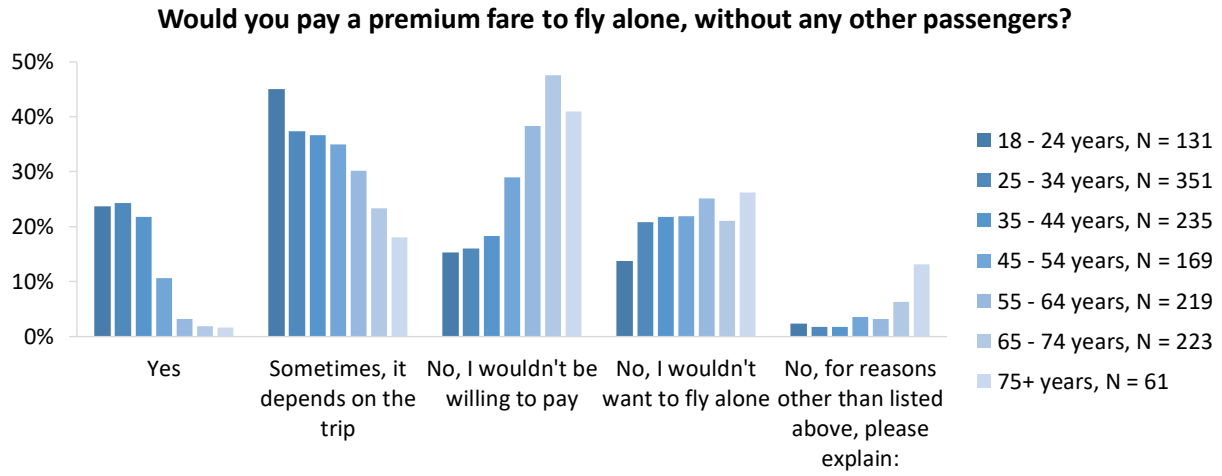


Figure 26: Willingness to pay a premium fare by age demographics

Next, the survey explored the security preferences among the respondents. Most of the respondents preferred routine security screenings for UAM flight. Only 8% of the respondents were unwilling to undergo a security screening process before each flight, and only 4% of the respondents did not want other passengers to undergo a security screening process. See Figure 84 in Appendix 1 – Societal Barriers (General Population Survey) for visual representation of respondents' security preferences. Respondents were also probed for potential trip purposes of UAM. Similar to the findings from the focus groups, respondents were most interested in using the technology for long-distance recreational trips (Figure 27).

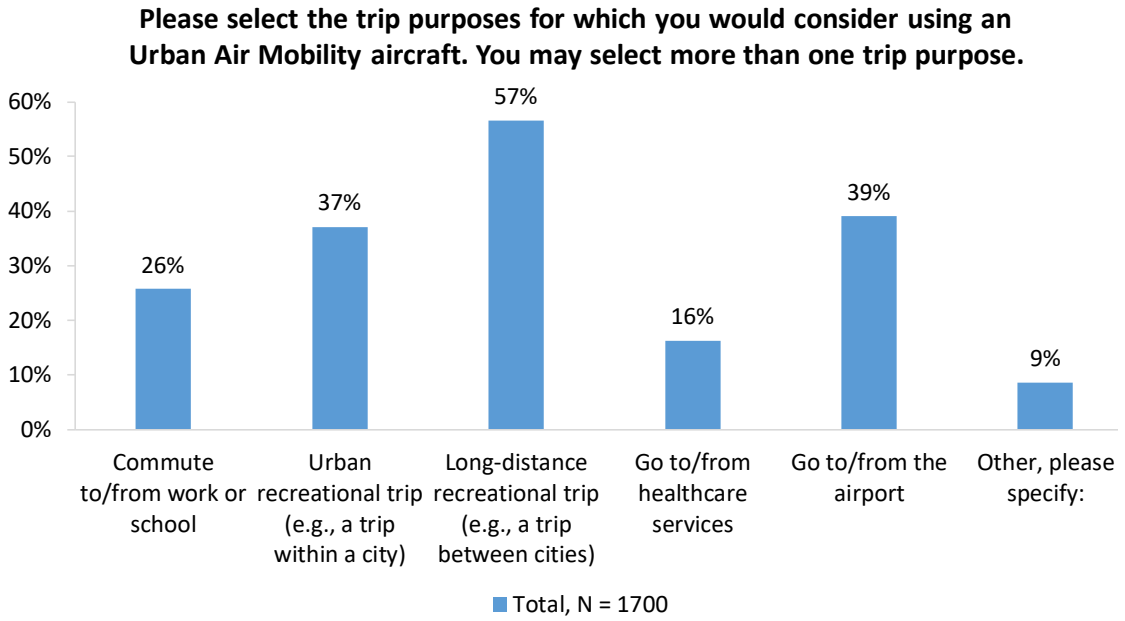


Figure 27: Responses to UAM trip purpose

For each trip purpose that respondents would consider using a UAM aircraft, we asked them to specify who they would likely travel with, if anyone (Figure 85 in Appendix 1 – Societal Barriers (General Population Survey). Most of the respondents planned to fly with friends, a spouse/partner, or alone.

Respondents were also asked a series of questions regarding their travel preferences in an automated future, where automated vehicles (AVs), shared automated vehicles (SAVs), and UAM are all present on

the market. Respondents were then asked questions regarding vertiports (specified landing/takeoff locations for UAM aircraft) and their use case preferences. For information on the survey findings from these questions, please see Appendix 1 – Societal Barriers (General Population Survey).

Many of the respondents (52% across the sample population) were not interested in owning a personal UAM aircraft, but 17% of respondents were interested in ownership. Men were more interested in owning a UAM aircraft than women (21% and 13%, respectively). We also explored whether the supply of UAM aircraft and pilots could be augmented through peer-to-peer (P2P) operations. For example, would owners of UAM aircraft be willing to rent out their aircraft or transport other people (similar to services, such as Lyft and Uber)? For those who answered "yes," "maybe," or "I don't know" to the question of interest in owning a personal UAM aircraft, there was high willingness to use the aircraft as part of a larger fleet service (e.g., Lyft, Uber). Approximately 44% of the sample respondents were willing to rent out their personal UAM aircraft for use by others. Los Angeles had a particularly high willingness to participate in shared mobility services – around 55% of those willing to own an aircraft were willing to also rent it out to others (i.e., a P2P service model). This suggests that perhaps there may be opportunity for P2P operations with UAM aircraft. However, respondents were not as interested in fractional ownership (i.e., shared ownership of a UAM among individuals) with only 20% of the sample respondents indicating willingness to share ownership of a UAM aircraft.

If P2P operations are to become a possibility, there will be a need for licensed pilots and people willing to fly UAM aircraft. The respondents were asked if they would be willing to fly a UAM aircraft, and approximately one in five respondents were willing. Los Angeles had an even higher percentage of respondents who were willing to fly a UAM aircraft at 30%. However, the survey population was heavily skewed toward those with pilot's licenses. Approximately one in five of the survey respondents claimed to possess a pilot's license, which is much higher than the national average. As of 2017, only 0.2% of U.S. residents were active certified pilots (FAA, 2018).

8.3.11 Perceptions from Non-User Perspective

We designed a set of questions that aimed to collect respondents' opinions from a non-user perspective. In other words, how would people on the ground feel about UAM traffic overhead? Would there be pushback from those not planning to use technology? Respondents were asked how they perceived a UAM taxi flying overhead if it was piloted, remote piloted, and automated. For the latter two types of UAM taxi, respondents were asked about flights overhead with and without flight attendants. Respondents tended to prefer flights that were piloted or that had a flight attendant on board (Figure 28) as their presence made non-users feel safer.

To gauge concern over noise, we probed the respondents' current experiences and perceptions about noise. The most common bothersome noises experienced by the respondents were noise from motor vehicles and neighboring properties, and they tended to be most bothered by noise at home. Respondents who reported being bothered by noise from aircraft tended to experience the most disturbance during the early morning hours and at night. Overall, respondents preferred that UAM technology have no noticeable noise. The noise levels of the technology could affect support for UAM.

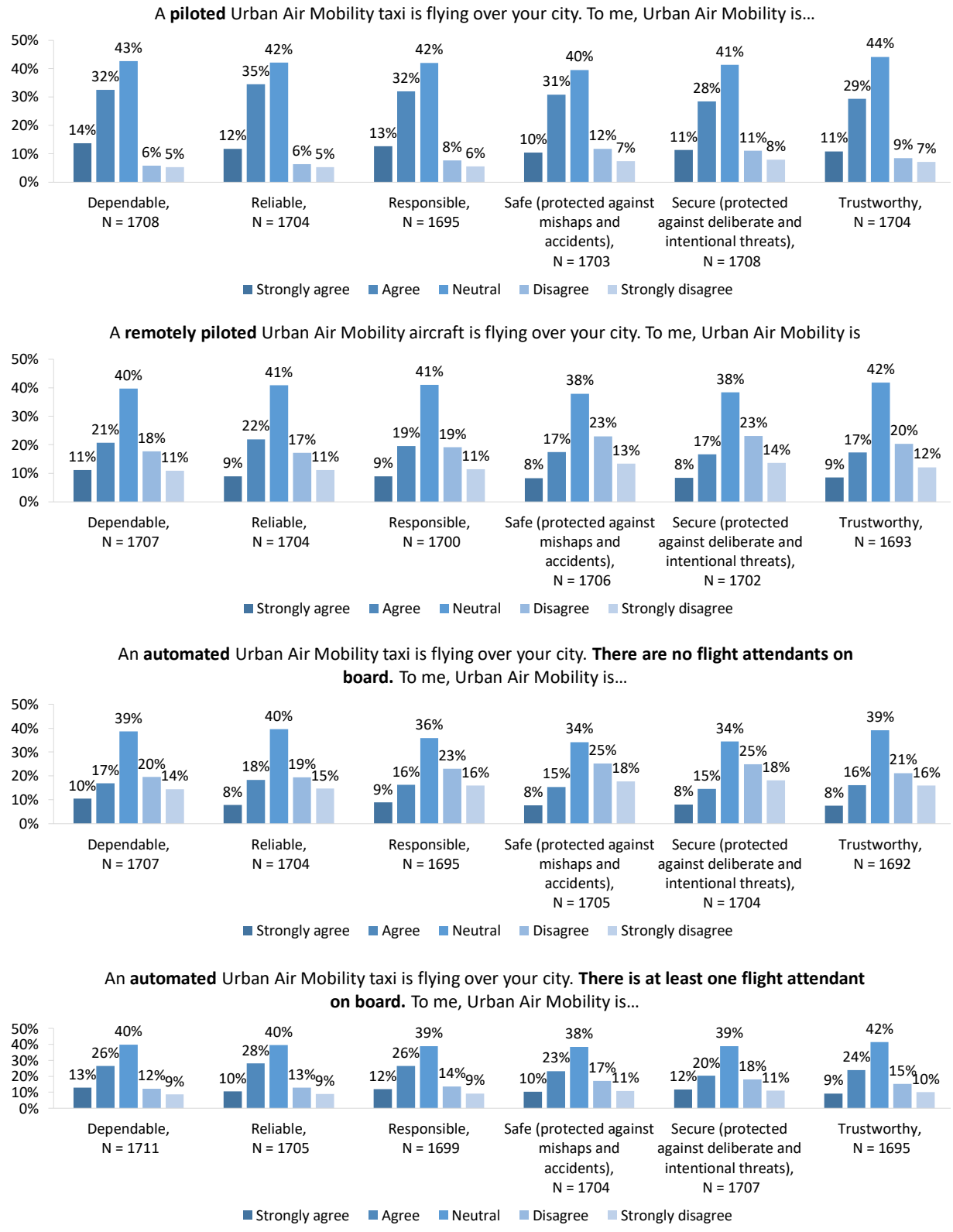


Figure 28: Perceptions from a non-user perspective

8.4 Societal Barriers Summary

Based on the findings of the exploratory survey administered to five metropolitan regions (Houston, Los Angeles, San Francisco Bay Area, New York City, and Washington, D.C.), the survey respondents were cautiously receptive to the concept of UAM. Initial reactions were clustered around excitement and happiness, neutrality, and skepticism. Overall, male respondents and young respondents tended to express more excitement over the technology, and they were also more willing to fly in a UAM aircraft. Familiarity with the UAM concept was also a strong factor influencing willingness-to-fly and a participant's decision on whether to take a UAM trip, suggesting that public education will play an important role in introducing UAM as a new travel mode.

Not surprisingly, the characteristics of a UAM trip impacted a respondents' feelings toward UAM. Respondents were more comfortable and willing to fly with passengers they knew in contrast to flying alone or with strangers. Willingness decreased with increasing levels of automation, and the presence of a flight attendant only slightly alleviated discomfort. The characteristics of the trip itself were also important. The respondents visualized themselves using UAM for longer trips and traveling to the airport. Long distance recreational trips were more popular than using a UAM for commuting.

While most of the respondents were not interested in UAM aircraft ownership, approximately 17% of the respondents expressed interest. In addition, almost half of the individuals attracted to ownership expressed significant levels of interest in placing their aircraft into a larger fleet service, opening the possibility for P2P UAM operations in the future.

For those on the ground, piloted UAM aircraft or automated/remotely piloted UAM aircraft with flight attendants on board were preferred for travel overhead. UAM will need to address concerns of trust, reliability, safety, and other issues to gain acceptance from non-users. Our results also indicate that noise levels could impact non-user support for UAM.

Key Findings	Key findings uncovered through the survey include: • Neutral to positive reactions to the UAM concept. Men, younger respondents, and wealthier respondents tended to be more excited. • The results from the ordinal logistic model with the dependent variable willingness-to-fly indicates age, gender, and familiarity with the UAM concept were the most significant characteristics affecting a person's stated willingness to fly. Younger, male respondents and those already familiar with UAM prior to the study were more willing to fly via UAM. • Results from Stated Preference (SP) questions also indicate that age, gender, and familiarity with the concept of UAM were statistically significant predictors of whether a person would take a UAM trip. These results are directionally the same as the ordinal model. • Results from the SP survey questions indicate respondents with higher incomes were more likely to take UAM trips. • None of the metropolitan areas displayed significance in the willingness-to-fly model; however, in the model derived from the SP questions, the coefficients for Los Angeles and the San Francisco Bay Area were statistically significant. Survey respondents from Los Angeles were more likely to agree to take a trip compared to respondents from Houston, and respondents from the San Francisco Bay Area were less likely to agree to take a UAM trip compared to respondents from Houston.

- Respondents were more receptive to using UAM for travel to the airport or long-distance recreational trips than for commuting.
- Respondents most comfortable flying with passengers they know; least comfortable flying with passengers they don't know.
- Some willingness and apprehension about flying alone (particularly in an automated/remote piloted context).
- Strong preference for piloted operations; may need to offer mixed fleets and/or a discount for remote piloted/automated operations to gain mainstream societal acceptance.
- The presence of a flight attendant did not impact willingness to fly on an automated or remote piloted UAM aircraft.
- Flight attendant did increase confidence in automated and remote piloted operations from the non-user perspective (someone on the ground).
- Preference for longer inter-city flights (e.g., Washington, D.C. to Baltimore; LA to San Diego).
- Survey and focus groups suggest some resistance to very short trips due to cost, convenience (e.g., required connections to/from vertiport; security screening; etc.).
- Some desire among younger and male respondents to pay a premium to fly alone.
- Some willingness to own and pilot UAM aircraft.
- Potential for a market for P2P operations that could help provide additional supply to scale the market (similar to Lyft and Uber).
- Existing noise concerns focus on traffic noise during the night and early morning; noise from UAM could pose a more notable obstacle in the future as electric vehicles become more mainstream (potentially causing a reduction in overall ambient noise making UAM more noticeable).

9.0 WEATHER BARRIERS

Weather constraints represent a critical and complex component of characterizing the UAM market. Weather can influence many components of UAM, including operations, service supply, passenger comfort, community acceptance, infrastructure, and traffic management. In this study, our goal was to provide an initial assessment of underlying historical weather conditions, or a climatology, which could impact UAM, with a focus on operations. No assumptions were made regarding vehicles or technology, so results could be made more precise by examining specific use cases in the future.

9.1 Methodology

This section will describe our weather analysis methodology used to develop the climatology, including data sources, generation of climatology at the ten focus urban areas, and consolidation of results into overall weather impacted hours.

9.1.1 Weather Data Sources

We first surveyed available data sources in and near focus urban areas, and found limited availability of high resolution, reliable (calibrated) observations collected directly in the urban areas. We therefore targeted regularly collected weather observations including Meteorological Aerodrome Report (METAR), vertical soundings, and pilot reports (PIREP) for our analysis. METAR are point observations collected hourly at the surface, most commonly at airports, and capture a wide range of conditions, including temperature, wind direction and speed, sky cover (low ceilings/visibility), and present weather (e.g., thunderstorms, rain, snow). Vertical soundings are generated from weather balloons that are launched twice a day from a fixed location, in morning (12Z) and afternoon (00Z) and provide conditions aloft which would be experienced during UAM flight or at an elevated vertiport. Data collected from these soundings include temperature, pressure, dew point, and wind speed and direction at multiple altitudes from the surface to about 65,000 ft. PIREPs are generated whenever a pilot encounters weather conditions that they deem impactful, such as low level wind shear or turbulence. These are not collected at a regular time interval, so they are used in this analysis as a supplemental source of weather impacts to augment signals observed from the METAR and vertical soundings.

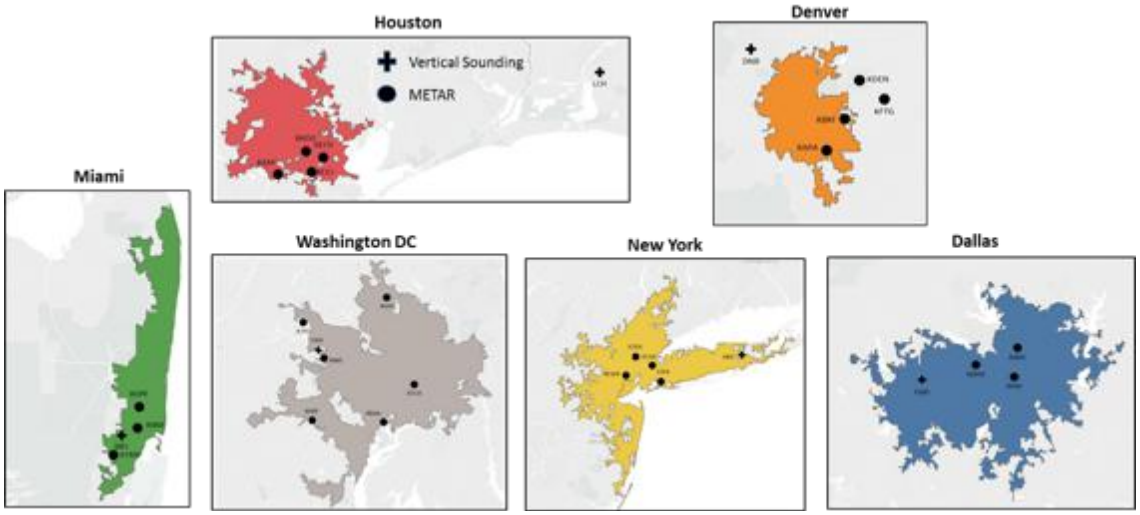


Figure 29: Surface and vertical sounding observation locations for 6 of the 10 target urban areas. Color shading area indicates spatial coverage of urban areas according to the U.S. Census

We evaluated the spatial extent and distribution of observation locations relative to the focus urban areas to assess how representative these data are of conditions and variability within the urban area. The METAR surface and vertical sounding observation locations overlap well with several of the target urban areas, but may not be fully representative of conditions in many. In most of the Eastern and Texas target urban areas, these observation locations are distributed evenly across the region while in some locations such as Miami

and Houston, the observations only capture conditions in one portion of the region (Figure 29 above). Furthermore, in some focus urban areas such as Denver, vertical sounding observations are collected outside of the urban area and may not fully represent conditions within the urban area. Despite these limitations, these observations provide a valuable baseline on historical adverse conditions in the target urban areas from which weather barriers to UAM can be assessed.

9.1.2 Historical Statistics

Weather conditions potentially impactful to UAM operations can vary strongly both diurnally and seasonally in many of our target urban areas, so we stratified our climatology by hour of the day and meteorological season – Winter (Dec, Jan, Feb), Spring (Mar, Apr, May), Summer (Jun, Jul, Aug), and Fall (Sep, Oct, Nov). We focused our analysis on the anticipated UAM operational window of 7 am – 6 pm Local Time to align with our economic market analysis, but have data for all 24 hours of the day.

For METAR surface observations, we computed statistics over a 7-year historical period (2010-2017) such as average temperature and frequency of conditions such as thunderstorms and Instrument Flight Rules (IFR) for each hour of the UAM operational window and each season. These statistics were first calculated and evaluated at each METAR location for an urban area to enable assessment of variability in adverse conditions at different locations within the urban area. For example, we found a significant difference in the frequency of winds greater than 20 kts in the San Francisco urban area during summer in the afternoon, with frequency greater than 50% at SFO (west of the Bay) but under 5% at OAK (east of the Bay) around 4 pm Local Time. This indicates that during this time and season, wind conditions are much more favorable for UAM operations in the eastern urban area than the western portion. We then calculated these statistics across all METAR stations in aggregate to analyze the seasonal variability in conditions across the urban area. Continuing the San Francisco example, we found that in aggregate, the frequency of winds greater than 20 kts is greatest (~20%) during afternoon in most seasons but only about 10% during winter indicating that across the urban area, wind conditions are slightly more favorable for UAM operations in winter.

As indicated earlier, the vertical sounding observations are only collected twice a day, so we computed seasonal averages across a 5-year historical period (2013-2017) for each of these two times (12Z and 00Z) at all target urban areas. Observations are collected at irregular vertical intervals as the balloon ascends, so we calculated average conditions in 500 ft bins to ensure sufficient sample size. Density altitude was computed from seasonal average conditions in the lowest available vertical bin at all urban areas to characterize lift conditions at vertiports. Average winds were generated by calculating the average North-South and East-West wind vector components of all historical winds in each altitude bin.

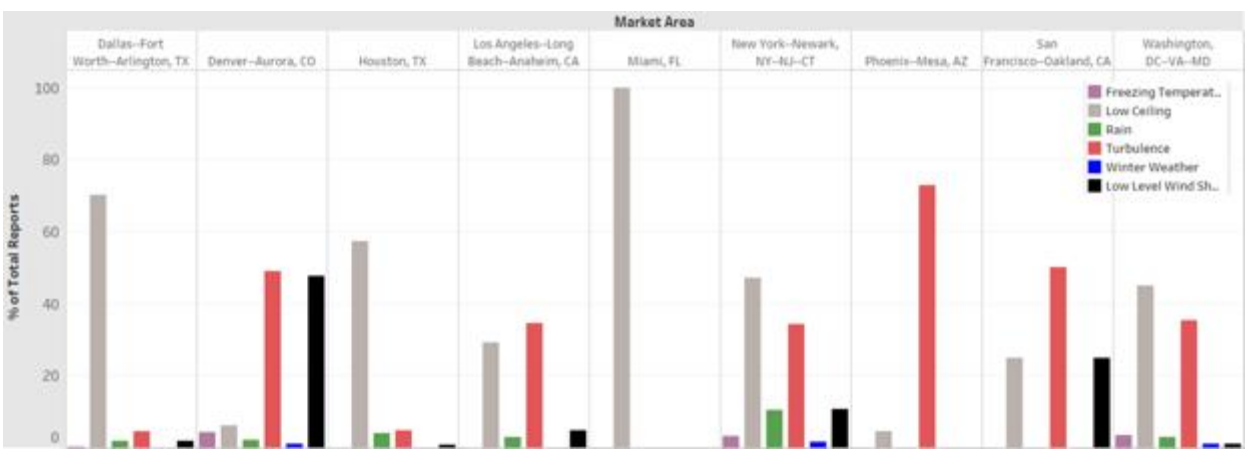


Figure 30: Distribution of PIREPs by weather condition at focus urban areas. No PIREPs were generated across our historical period in Honolulu

Pilot reports were used as supplemental observations to augment results from the surface and vertical sounding observations due to their ad hoc collection. We first isolated PIREPs across a 3-year historical period (2015-2017) over or near the focus urban areas using the airport code in the reports. Within each urban area, we then computed the percentage of reports with each type of reported weather to identify which conditions were most prevalent (Figure 30 above). Across all urban areas, low ceilings and

turbulence were the most frequently reported conditions with low level wind shear being reported somewhat frequently at several urban areas including Denver and San Francisco. Because more than one condition may be included in a given report, these percentages may not always add up to 100%.

9.1.3 Impacted Hours

After generating detailed statistics on historical weather conditions individually, we lastly computed the overall average number of hours that UAM operations would potentially be significantly impacted based on the underlying conditions. The goal of capturing these impacted hours is to provide a consolidated metric for weather impacts during the UAM operational day at each urban area. The impacted hours were generated based on METAR surface observations as they provide the highest temporal resolution (hourly) of all our data sources.

To do this, we first defined "impact scores" for each weather condition captured in METAR observations, from 1 (minimally impactful, little reduction in operations) to 10 (significantly impactful, potential cessation of operations). We leveraged our extensive expertise in aviation weather as well as available literature on weather influence on UAS and UAM vehicles to define these scores which are shown in Table 10. These scores are preliminary and were defined to capture potential impacts across a wide range of UAM operations and make no assumptions about components such as vehicle type or level of automation. Further refinement and precision of the weather impact scores could be achieved through case studies where these components are explicitly defined. Vertical wind shear is a critical condition that will likely impact UAM operations which cannot be directly quantified from surface observations. These impact scores could be extended by leveraging higher temporal resolution vertical data such as airborne observations from commercial aircraft.

Table 10: Impact Scores for each weather condition from METAR

Weather Condition	Score		Weather Condition	Score
Drizzle	1		Wind 20 - 25 kts	7
Rain	1		Smoke (<3 sm)	7
MVFR Ceiling	1		LIFR Ceiling	7
Haze	1		IFR Visibility	7
Ice Crystals	1		Wind ≥ 25 kts	8
Sand Whirls	1		Sleet	8
Sand	2		Squalls	8
Snow Grains	2		Fog	8.5
Temp ≤ 32°F	3		Freezing Fog	8.5
Temp ≥ 100°F	3		Freezing Drizzle	9
IFR Ceiling	4		Thunderstorms	9
Dust	5		Dust Storm	10
Snow	5		Funnel Cloud/Tornado	10
Sandstorm	5		Freezing Rain	10
Wind 15 - 20 kts	5		Hail	10
Mist (vis >= 5/8 sm)	6		Volcanic Ash	10
Snow Pellets	6			

We then computed the average impact score at each hour of the UAM operational day for each season at all target urban areas, based on conditions that occurred historically during that hour. To define an hour of the UAM operational day as "impacted", we needed to define an average impact score threshold. We evaluated variability of the average impact score distributions, as well as the impact scores themselves, and determined that an average impact score threshold of 3 provided a robust delineation between minimal and significant potential impacts to UAM operations. This threshold could be further refined with additional analysis, and also through application of specific assumptions about UAM operations (e.g., vehicle type). Therefore, if the average impact score for any hour of any season exceeded 3, we considered that hour to be potentially impacted by weather, or an "impacted hour". The number of impacted hours was lastly summed across the UAM operational day for each season. For example, the average impact score during summer at San Francisco exceeded 3 from 1-6 pm Local Time, leading to a total of 6 weather impacted hours (Figure 31).

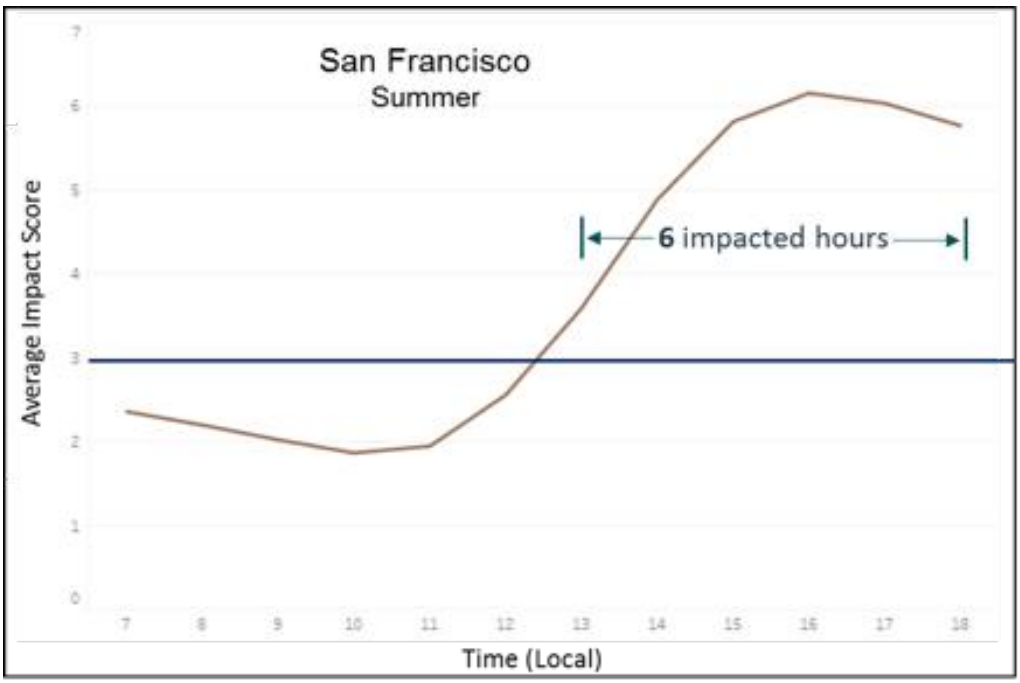


Figure 31: Average impact scores for each hour of UAM operational day at San Francisco urban area in summer

9.2 Results

This section will describe our results, focusing on key signals including high historical frequency of potentially impactful weather conditions, variability in conditions within an urban area as well as diurnally and seasonally, and average number of impacted hours. Because the sample size of historical PIREPs was not sufficient to evaluate seasonal or diurnal variability in conditions, we evaluated the spatial distribution of reported conditions in each urban area to augment signals observed from surface and vertical soundings. Results will be presented for urban area regions first, followed by density altitude across all urban areas, and lastly impacted hours. Supplemental figures to augment results presented here can be found in Appendix 2 – Weather Analysis.

9.2.1 Western Urban Areas

Overall, weather conditions are favorable for UAM operations at most western focus urban areas. In Honolulu, surface winds above 20 kts are the only potentially impactful condition with a relatively high frequency of occurrence (9-10%) in early afternoon during spring and summer (Figure 91 in Appendix 2 – Weather Analysis). Phoenix experiences several weather conditions on average that may be impactful to UAM, including high temperatures, strong winds, and thunderstorms (Figure 92 in Appendix 2 – Weather Analysis). These unfavorable conditions occur most frequently during afternoon in summer. Most pilot reports in Phoenix were due to turbulence and were uniformly distributed spatially across the urban area. In the Los Angeles urban area, weather conditions are mostly favorable for UAM operations, though IFR conditions are somewhat frequent in morning, especially during summer (Figure 93 in Appendix 2 – Weather Analysis). There was also variability within urban area during summer, where historical IFR frequency was above 50% in early morning at LAX while only about 20% at Van Nuys (Figure 32). Most PIREPs were due to turbulence, located mostly over the ocean, and low ceilings, located mostly in the western urban area which is consistent with findings from METAR observations.

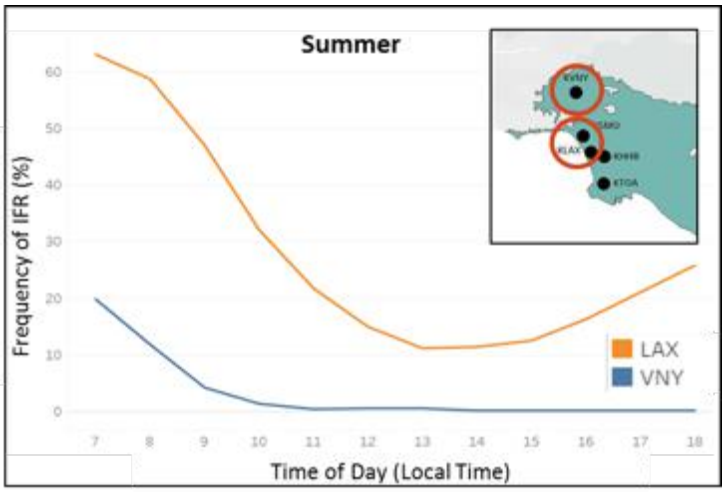


Figure 32: Hourly summer frequency of IFR conditions at LAX (orange) and VNY (blue) in Los Angles urban area

We also found variability in conditions within the San Francisco urban area, which frequently experiences IFR and winds above 20 kts in most seasons (Figure 94 in Appendix 2 – Weather Analysis). The frequency of winds above 20 kts is significantly greater at SFO than OAK in all seasons except for winter (Figure 33). This suggests that wind conditions are more favorable for UAM in the eastern portion of the urban area during afternoon hours. IFR conditions also have a high historical frequency during morning hours, exceeding 60% before 8 am Local Time in summer.

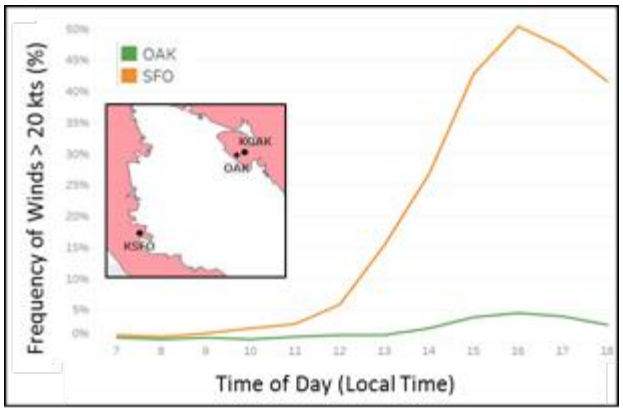


Figure 33: Hourly summer frequency of winds above 20 kts at SFO (orange) and OAK (green)

In Denver, average weather conditions are unfavorable for UAM operations during most hours and seasons (Figure 95 in Appendix 2 – Weather Analysis). Cold temperatures (below freezing) which may reduce passenger comfort and influence vehicle battery life are possible during fall, winter, and spring especially in the morning hours. IFR conditions are

also somewhat frequent (15%) during the morning across all seasons, with lowest frequency occurring during summer. Thunderstorms and strong winds are common during afternoon in summer, which could compromise safety of UAM operations. Strong average winds aloft (5000 ft) were also observed during all seasons on average, which could influence UAM mission duration and vehicle spacing (for large scale operations). Denver is also one of the few focus urban areas where PIREPs were generated for all types of weather conditions (Figure 96 in Appendix 2 – Weather Analysis). Turbulence and wind shear were the most frequently reported conditions and were distributed uniformly across the urban area spatially.

9.2.2 Eastern Urban Areas

Average weather conditions were found to be less favorable in the Eastern focus urban areas than the Western areas. In Washington, D.C., thunderstorms and IFR conditions are the most frequent potentially impactful weather. IFR conditions are on average most common in the early morning during all seasons while thunderstorms occurred most often in afternoon during summer (Figure 97 in Appendix 2 – Weather Analysis). Most PIREPs were due to turbulence and low ceilings, the majority of which were reported while departing out of IAD in the western portion of the urban area (Figure 98 in Appendix 2 – Weather Analysis).

Several adverse conditions were frequent in the New York urban area for most hours and seasons, which included IFR, winds above 20 kts, and rapid changes in wind speed with altitude, or vertical wind shear (Figure 99 in Appendix 2 – Weather Analysis). Variability in strong winds was observed within the urban area, with JFK (on Long Island in eastern portion of the urban area) experiencing the highest frequency of winds above 20 kts during afternoon (~14%) while a significantly lower frequency of occurrence (~2%) was observed at TEB (northern portion of urban area). Across the urban area in aggregate, IFR conditions are frequent (20-25%) during all seasons in early morning. Wind shear was also observed during morning in winter, with average wind speed increasing from only a few knots at the surface to almost 20 kts around 1000 ft altitude which could impact UAM during takeoff and in flight. Similar to Washington, D.C., most PIREPs in the New York urban area indicated turbulence and low ceilings (Figure 100 in Appendix 2 – Weather Analysis).

Overall, average weather conditions in the Miami urban area were favorable for UAM operations. Thunderstorms occurred frequently during early afternoon in summer and fall, while IFR conditions were somewhat common during winter in the early morning hours (Figure 101 in Appendix 2 – Weather Analysis).

9.2.3 Texas Urban Areas

In the two Texas urban areas, frequent thunderstorms, IFR, and vertical wind shear conditions pose potential challenges for UAM operations in most seasons. In Houston, we found some variability in IFR condition frequency within the urban area (Figure 102 in Appendix 2 – Weather Analysis). These conditions are most frequent during morning in winter and spring overall, but have a higher frequency at IAH (over 35%), in the northern part of the urban area, than at HOU (20%) which is in the southern portion of the urban area. High surface air temperatures, which may impact passenger comfort, are possible in summer and early fall. Thunderstorms were also frequent in early afternoon during summer, which would impact safety of UAM operations. We also saw that a strong low level jet, or altitude band with strong winds, was commonly present around 2500 ft in morning during winter along with strong winds near 5000 ft.

Average weather in the Dallas urban area was similar to Houston, with high temperature, IFR, thunderstorms, and strong low level jet being the most frequent potentially impactful conditions to UAM (Figure 104 in Appendix 2 – Weather Analysis). The frequency of IFR conditions during morning in fall and summer was higher in Dallas than Houston, but still less frequent than in winter and spring. We also found that thunderstorms were more common during afternoon in spring than in Houston, possibly due to passage of strong cold fronts that are frequent during spring.

9.2.4 Density Altitude

The average density altitude for all target urban areas in each season, calculated from conditions in the lowest altitude bin of the vertical sounding data, is shown in Table 11 along with the field elevation from which the observations were taken. These values are greatest for all urban areas during summer, when temperature is typically highest. Phoenix has the highest average summer density altitude relative to surface elevation above sea level (~2000 ft), which may result in impacts to UAM takeoff and lift. Average

density altitude is also about 1000-2000 ft above surface elevation in Miami during both summer and fall, and Dallas, Denver, and Houston during summer.

Table 11: Average seasonal density altitude for focus urban areas.

Urban Area	Field Elev. (ft)	Spring	Summer	Fall	Winter
New York	65	-968	645	-618	-1976
Washington, D.C.	305	-152	1264	27	-1384
Miami	16	779	1281	1026	484
Dallas	561	682	2055	786	-460
Houston	33	436	1342	527	-349
Denver	5285	5742	6974	6025	4759
Phoenix	2464	3660	4614	3830	2641
Los Angeles	397	3	30	36	-9
San Francisco	10	-115	343	217	245
Honolulu	98	1039	1498	1248	885

9.2.5 Weather Impacted Hours

As described earlier, we lastly computed the overall average number of weather impacted hours during the UAM operational day (7 am – 6 pm Local Time) for each season across all focus urban areas. These weather impacted hours are shown in Table 12, along with the average across all seasons in the rightmost column. According to the average values across the seasons, approximately half of the UAM operational day would potentially be impacted by weather on average at most target urban areas including New York, Washington, D.C., Dallas, Houston, Denver, and Honolulu.

We found a high number of weather impacted hours, sometimes more than half of the UAM operational day, occurred during winter and spring in the Northeast, Texas, and Denver urban areas. Conversely, most urban areas experienced the fewest impacted hours during summer and fall with the exceptions being Honolulu and Phoenix. Due to the high frequency of several impactful conditions during summer in Phoenix, including thunderstorms and high temperatures, almost half of the operational day would potentially be influenced by adverse weather during summer. In Honolulu, the high frequency of strong winds through most of the operational day during summer results in nine weather impacted hours during summer.

Despite historical occurrence of adverse conditions like thunderstorms, the number of weather impacted hours in Miami was zero for all seasons. This is due to the fact that the underlying frequency of thunderstorms was sufficiently low that the average impact scores for all hours of the UAM operational day fell below our threshold of 3. These results would benefit from refinement of our impact scores to capture the fact that underlying frequency of occurrence is different for all phenomena, with smaller values expected for small scale, short-lived conditions like thunderstorms.

Table 12: Average number of weather impacted hours for all target urban areas by season

Urban Areas	Winter	Spring	Summer	Fall	Average
New York	12	12	0	8	**8**
Washington, D.C.	12	12	0	0	**6**
Miami	0	0	0	0	**0**
Dallas	11	12	3	0	**6.5**
Houston	9	11	0	0	**5**
Denver	12	12	4	3	**7.75**
Phoenix	0	0	5	0	**1.25**
Los Angeles	2	1	2	1	**1.5**
San Francisco	3	6	6	4	**4.75**
Honolulu	0	7	9	6	**5.5**
Average	**6.1**	**7.3**	**2.9**	**2.2**	

9.3 Weather Barriers Summary

Key Findings

We found the following key results from the weather barriers analysis:

- Weather most favorable for UAM operations in Western focus urban areas, which experience weather impacted hours for less than half of the operational window mostly due to frequent high temperatures and IFR conditions during summer and strong surface winds
- Weather conditions highly unfavorable for UAM operations in Denver due to frequent adverse weather in all seasons
- Approximately half of the UAM operational day potentially impacted by weather on average in Texas urban areas due to thunderstorms, IFR conditions, and vertical wind shear
- Weather conditions less favorable in New York and Washington, D.C. focus urban areas as potential for most of operational day to be impacted by weather on average across all seasons primarily due to IFR conditions, strong surface winds, and vertical wind shear
- Weather favorable for UAM operations in Miami, though thunderstorms could cause short term disruptions mostly in fall and summer

10.0 AIRPORT SHUTTLE AND AIR TAXI MARKET ANALYSIS

The Booz Allen team approached the analysis of Airport Shuttle and Air Taxi markets using a system-of-system framework. As shown in Figure 34, the UAM ecosystem can be conceptualized as a set of system level layers including: supply (in terms of technology and UAM transport services), demand for UAM services, infrastructure (in terms of location and capacity of vertiports), legal/regulatory environment, and the general public. Each system layer and connections between them are investigated using a scenario and Monte Carlo based sensitivity analyses framework. For the purpose of this study, we calculated and tracked key metrics from the perspective of operators (e.g., number of flights, potential revenue and operating costs), passengers (e.g., number and distribution), non-flying public (e.g., flight patterns, potential noise impacts), and infrastructure providers (e.g., number, location and capacity of vertiports).

Figure 34 shows the block diagram describing the multi-step process used to analyze the UAM markets. This included:

- ***Step 1: Definition of concept of operations (ConOps):*** An air taxi mission is defined based on requirements in terms of mission range, demand, infrastructure availability, and vehicle capabilities, among others. A concept of operations (ConOps) was also designed to capture the activities completed by the passenger and air taxi to complete one mission. The ConOps included ground transportation for first last mile service, transfers, and air taxi flight.
- ***Step 2: Development of operating model and calculation of key performance metrics:*** Cost of service for passengers was calculated for different vehicle type proposed to serve the Air Taxi market. Each relevant cost component like capital and maintenance cost, energy and battery cost, and infrastructure cost, among others were individually modeled. Weather related adjustments like wind speed, temperature, and density for each urban area was applied. Having calculated the cost of service for passengers, the next step in the loop was to calculate demand using a five-step process: Trip Generation, Scoping, Trip Distribution, Mode Choice, and Operational constraints.
- ***Step 3: What if Scenario Analyses:*** As described in the introduction to this section, the UAM market is at the initial stage of development and its emergence will be driven by several factors. The potential effects of a several factors were tested to understand the implications to market size and viability. These included: operational constraints including capacity of available infrastructure, time of day restrictions on operations to minimize impact on public, and regulatory hurdles to fly under Instrument Flight Rules (IFR) conditions.
- ***Step 4: Monte Carlo based Sensitivity analyses:*** In order to assess the propagation of input uncertainties on key performance metrics to better understand the potential market size and its viability, Monte Carlo based sensitivity analyses were conducted. This involved randomly generating 10,000 missions for each urban area. Eight scenarios were developed based on current state and future state of air taxi system of systems and decisions and actions by key stakeholders.

10.1 Design Mission and ConOps

As input to the system level analysis of the UAM market, operational concepts and typical missions were developed. Figure 35 shows a step-by-step notional ConOps as defined in this analysis. In comparison to the same trip performed by ride-hailing service on ground, passengers using UAM service (i.e., air taxi or airport shuttle) undergo the following transfers: Origin to Heliport (or Vertiport) using ground transportation, Heliport (closer to the origin) to Heliport (closer to the destination), and Heliport to Destination using ground transportation.

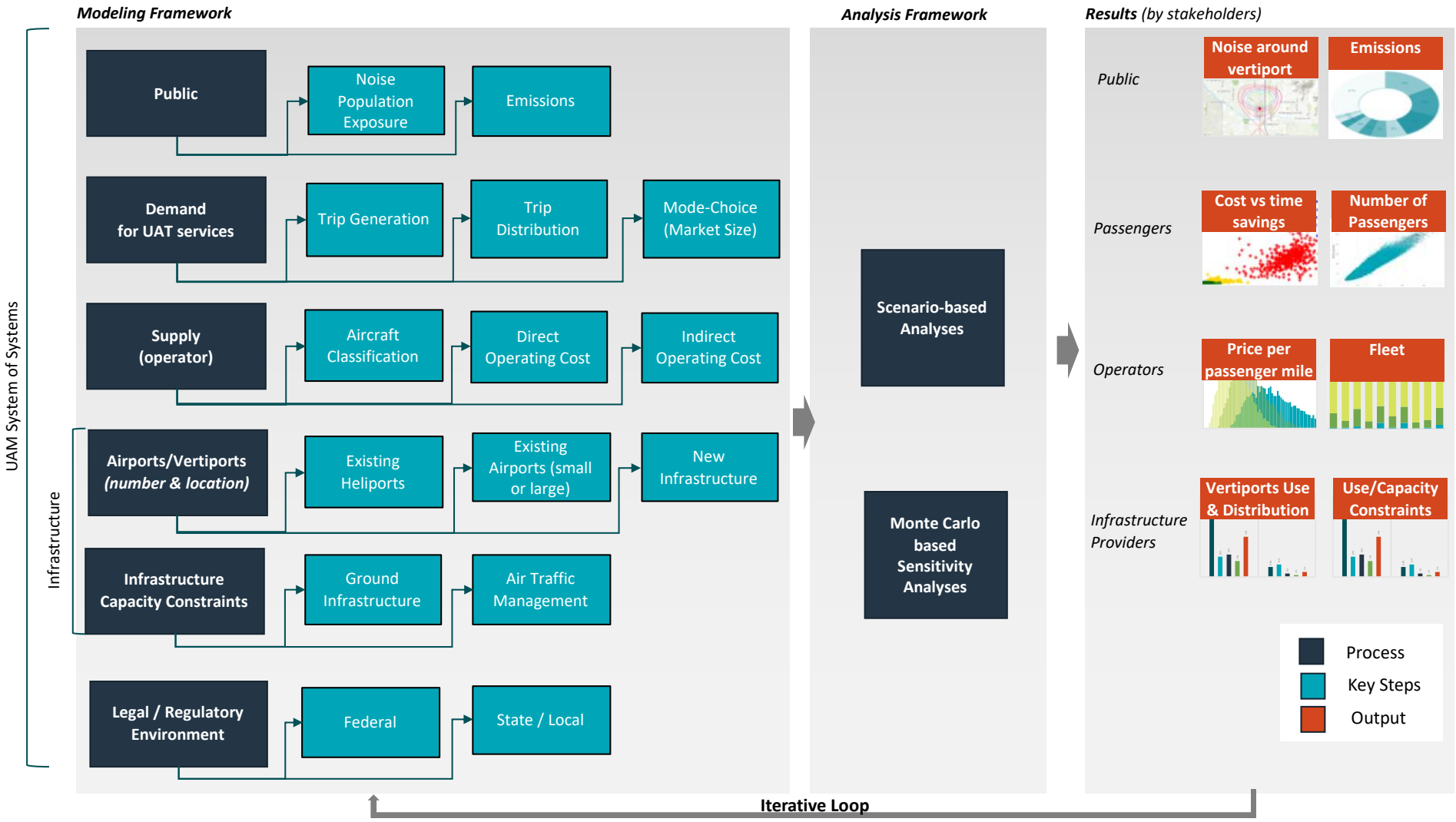


Figure 34: Modeling framework for Airport Shuttle and Air Taxi Analysis

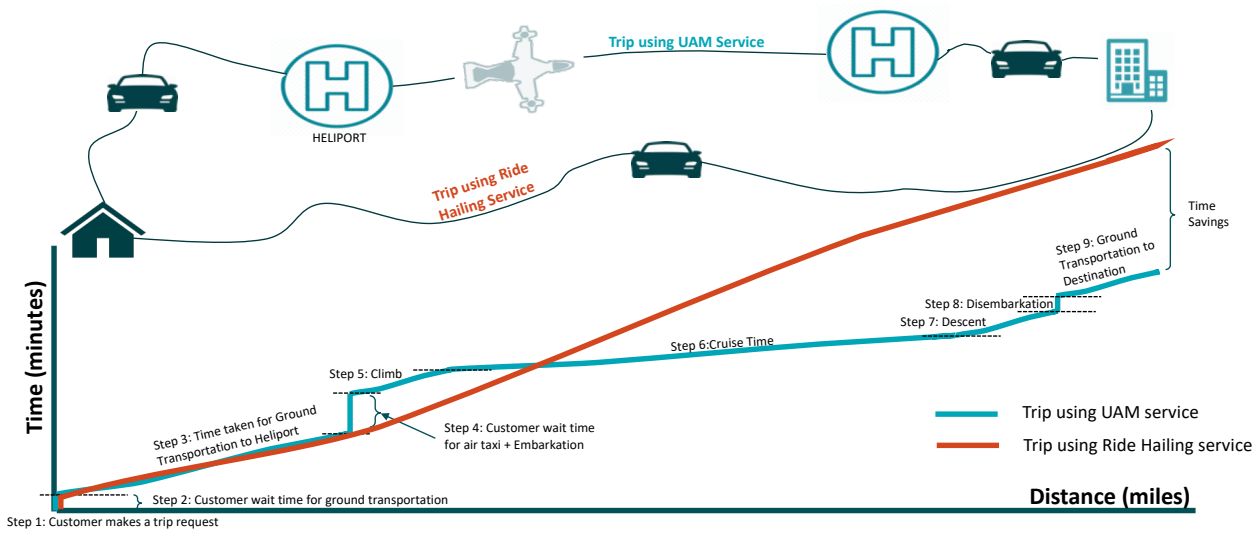


Figure 35: Notional ConOps for Air Taxi and Airport Shuttle mission

As shown on Figure 36, a typical Airport Shuttle and Air Taxi mission comprises five main phases of flight: take-off, climb, cruise, descent, and landing. Taxi time is added at both the origin and the destination. An additional transition phase (vertical to horizontal flight) is added between take-off and climb phase for tilt rotor, tilt wing, and tilt duct type of aircraft. There is no horizontal movement considered during the transition phase. In this study, reserve mission kicks off during the descent phase and follows a similar profile as original mission i.e., take-off, climb, cruise (at cruise altitude and cruise speed), descent, and landing at another landing area (l_2').

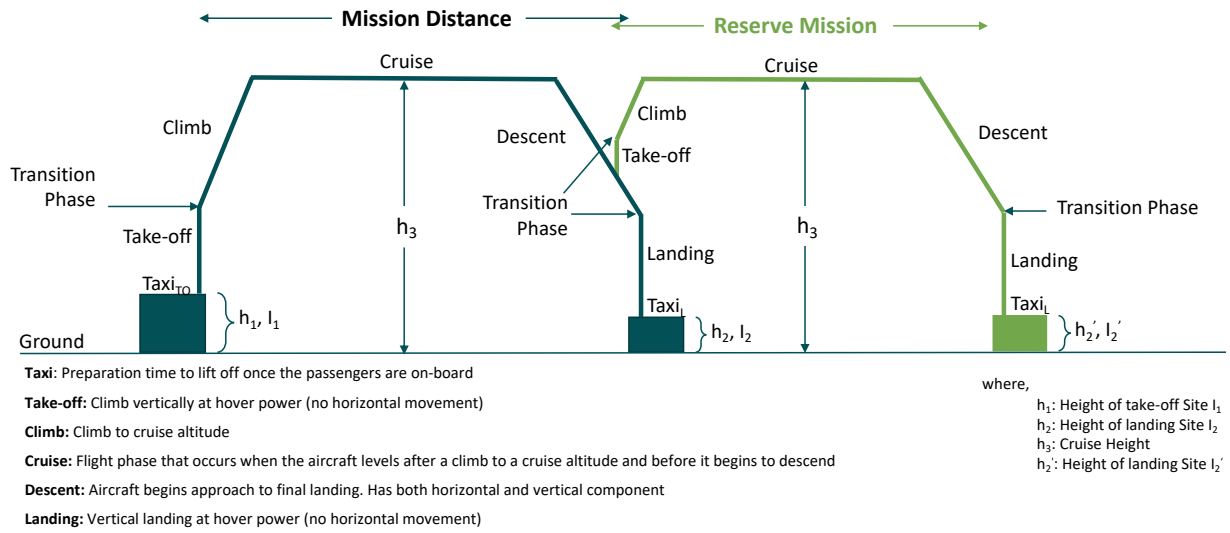


Figure 36: Mission profile of Airport Shuttle and Air Taxi mission

10.2 Key Operations Related Assumptions

For the purpose of this analysis and based on interactions with SAG members, we assumed that for the first few years of operations, a pilot on-board will control the aircraft assuming no autonomy. Among other assumptions highlighted in Table 13 below for the Monte Carlo analysis, we expected Air Taxis and Airport Shuttle to serve a longest mission of 50 miles with a single charge.

Table 13: Operations Related Assumptions for Monte-Carlo (first few years of service)

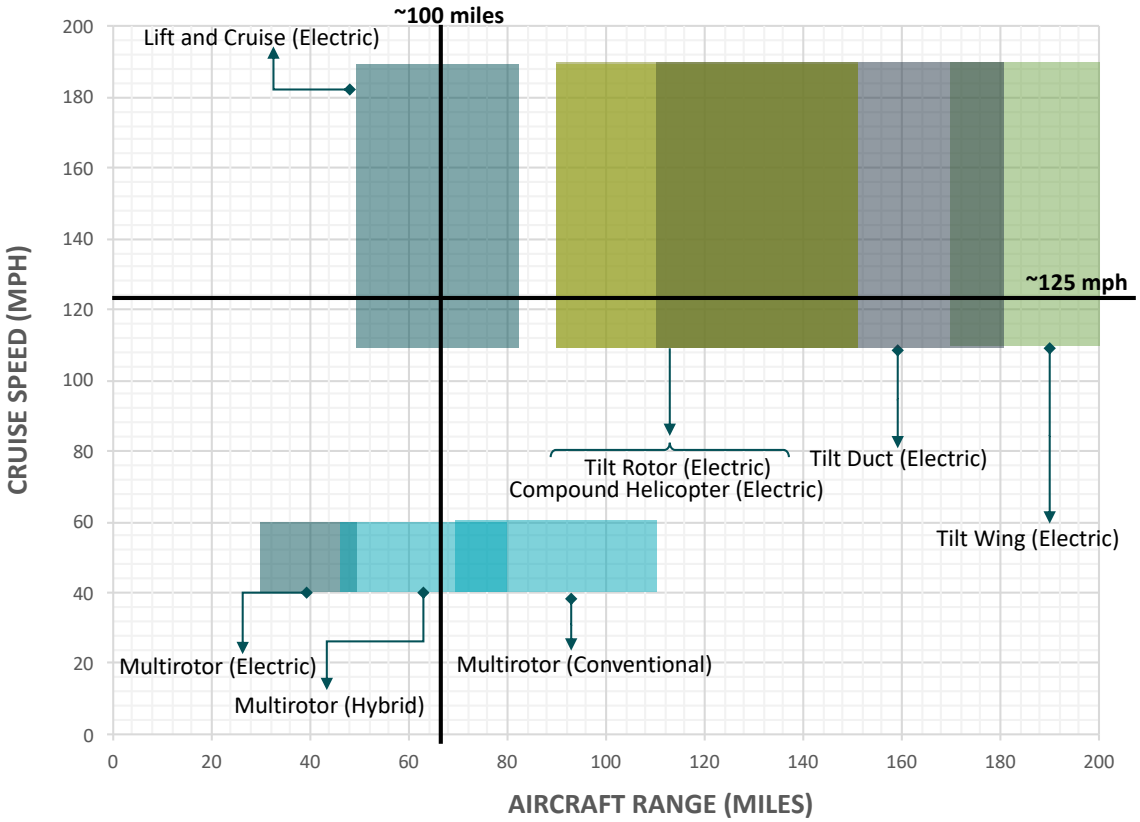
Parameter	Definition	Minimum	Maximum
Aircraft Seats (Passenger seats = Aircraft Seats -1)	Number of seats in aircraft. Initial years of operation assumed a pilot on-board, hence there was one seat less available to be occupied by a passenger	1	5
Load Factor (%)	Passenger load factor which measures the utilization of the capacity of the eVTOL i.e., number of seats occupied by a revenue passenger divided by total number of available seats	50%	80%
Utilization (annual number of flights) for 2+ seat aircraft (number of flight hours per year)	Average numbers of hours in a year that an aircraft was actually in flight. Conservative utilization numbers were used to consider battery recharging/swapping times	1000	2000
Utilization (annual number of hours) for 2 seat aircraft (number of flight hours per year)	For 2-seat aircraft (only one passenger seat), aircraft was only flown when the passenger seat was filled. Therefore, utilization range was adjusted by multiplying with load factor of 2+ seat aircraft i.e., 1000*50%, 2000*80%	500	1600
Max Reserve (mins)	Flight time for reserve mission (outside of mission time) at a specified altitude	20	30
Deadend Trips (%)	Ratio of non-revenue trips and total trips	25%	50%
Detour Factor (%)	Factor that captures the lateral track inefficiencies equal to ratio of actual flight distance divided by great circle distance between two vertiports	5%	15%
Cruise Altitude (ft)	Cruise altitude for UAM vehicles	500	5000
Embarkation time (mins)	Time spent in the process of loading UAM vehicle with passengers and preparing them for flight	3	5
Disembarkation time (mins)	Time required for passengers to disembark the UAM vehicle after the flight	2	3
Battery Depth of Discharge (%)	Referred to the degree to which a battery was discharged in relation to its total capacity	50%	80%

10.3 Price per passenger mile

The Booz Allen team analyzed nine different vehicle types (Figure 37) with Electric, Hybrid, and JetA powertrains proposed to serve broader UAM market:

(1) ***Multirotor*** - Rotorcraft with more than two rotors (e.g., Ehang and Volocopter)

(2) ***Autogyro*** - Type of rotorcraft that uses an unpowered rotor in free autorotation to develop lift (e.g., Carter)



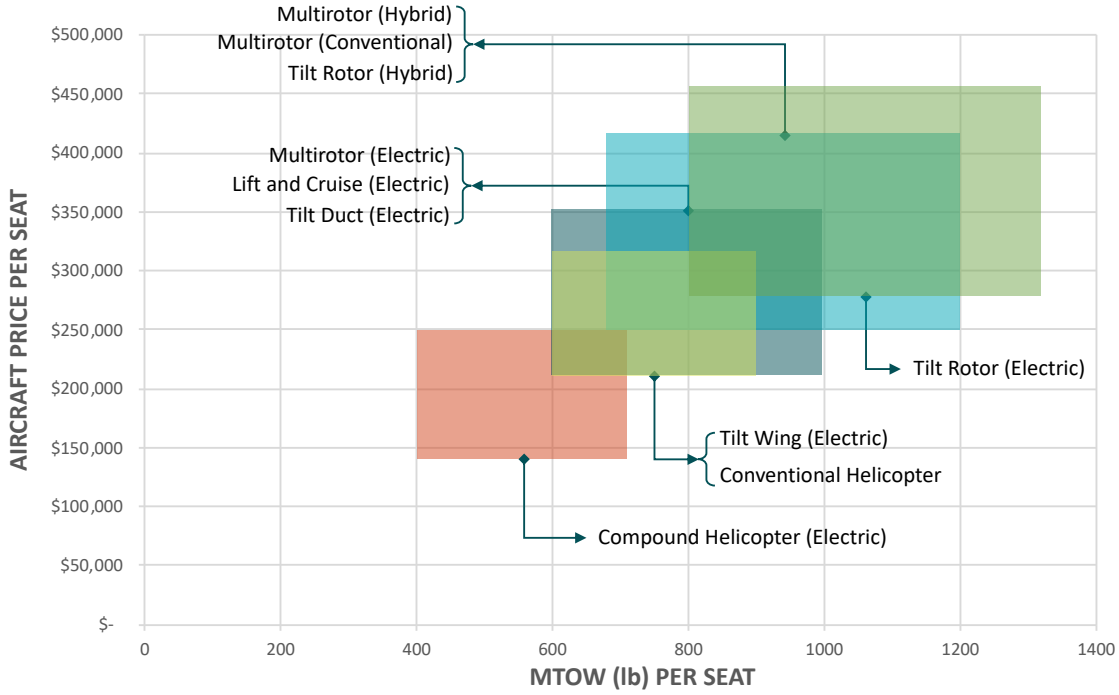


Figure 37: Technical specifications of the vehicle types with uncertainty ranges; (top) Cruise Speed (mph) vs Range (miles), (bottom) Aircraft Price vs MTOW (lbs.)

(1) ***Conventional Helicopter*** – Type of rotorcraft in which lift and thrust are supplied by rotors (e.g., Robinson R22)

(2) ***Tilt Duct*** – eVTOL in which a propeller is inside a duct to increase thrust (e.g., Lilium Jet)

(3) ***Coaxial Rotor*** – Rotors are mounted one above the other (e.g., GoFly)

(4) ***Lift + Cruise*** – Has independent thrusters for cruise and lift (e.g., Aurora Flight Sciences)

(5) ***Tilt Wing*** – Aircraft uses a wing that is horizontal for conventional forward flight and rotates up for vertical takeoff and landing (e.g., A^3 Vahana)

(6) ***Compound Helicopter*** – Includes helicopter rotor-like system and one or more conventional propellers to provide forward thrust during cruising flight (e.g., HopFlyt)

(7) ***Tilt Rotor*** – Aircraft type which generates lift and propulsion by way of one or more powered rotors mounted on rotating engine pods or nacelles (e.g., Joby Aviation)

Each vehicle type has distinct performance characteristics. For example, Tilt Ducts have significantly higher disk loading (i.e., higher engine power will be required to hover while Multirotor has significantly low lift to drag ratio indicating lower performance). For the purpose of this analysis, the airport shuttle and air taxi markets were evaluated using electric vehicles/technology due to potentially lower environmental impact, lower dependence on fluctuating fuel prices, and lower operating costs. Therefore, we focused our supply side analysis on the electric version of the mentioned vehicle types (Autogyro and Coaxial Rotor were not considered due to unavailability of sufficient data) and refer to them as electric VTOL (eVTOL). Next, we reviewed 70+ designs from the publicly available sources and developed technical specifications like speed, range, and weight, among others of reference vehicle for each of the remaining vehicle types as shown in Figure 37. Aircraft specifications like vehicle cost and maximum take-off weight (MTOW) were calculated on per seat basis and were simply extrapolated for aircraft with more than one seat.

Having developed reference vehicles for each vehicle type, the next step was to operate these vehicles on a randomly generated design mission. We followed a ride-sharing business model (i.e., one or more passenger travels in an eVTOL and pays on a per passenger mile basis). All passengers are picked up at the origin vertiport and are dropped-off at the destination vertiport. Ground transportation further provides first and/or last mile service.

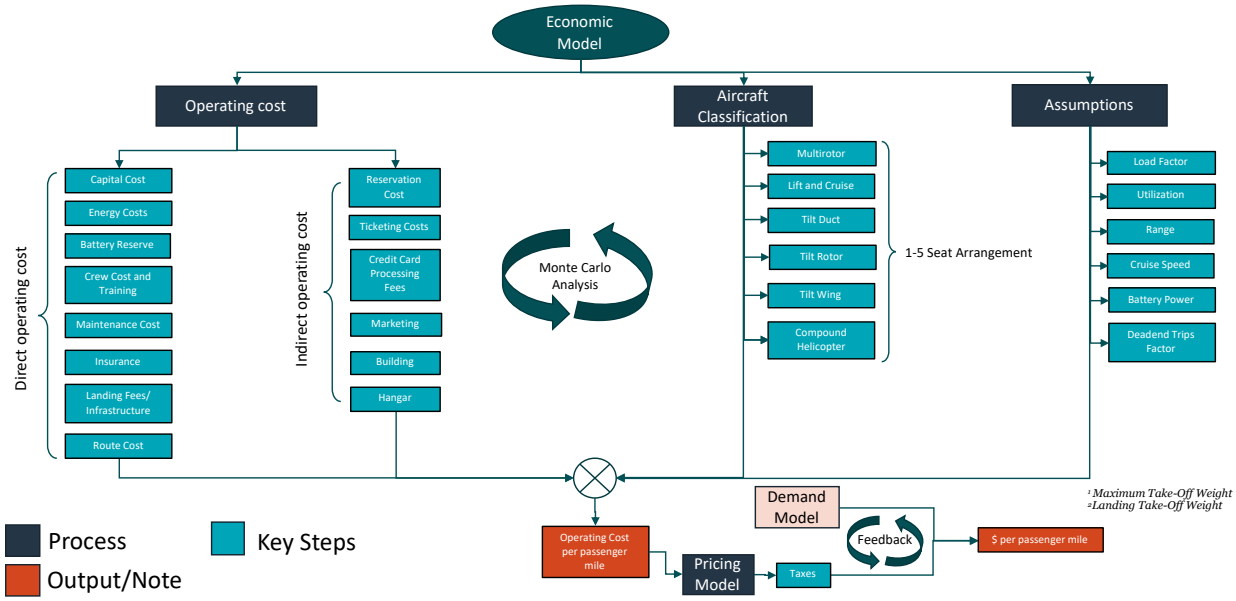


Figure 38: Structure of Supply Economic Model for an eVTOL

Next, the operating cost per passenger mile for each reference vehicle was calculated as a sum of direct operating cost (DOC) and indirect operating cost (IOC). DOC includes capital, energy, battery, crew, maintenance, insurance, infrastructure, and route cost, while IOC includes marketing and reservation costs. Next, we applied a pricing model and taxes to calculate price per passenger mile (i.e., cost to passenger). Each of the cost components of DOC were individually modeled for aircraft with 2-5 seats (1-seat aircraft was not considered due to pilot requirement), while IOC was calculated as percent of DOC (10-30%). To conduct the Monte Carlo based sensitivity analysis, 10,000 randomly generated iterations were performed. Table 14 shows key steps and the uncertainty ranges and assumptions used in modeling of each of the cost component. Detailed assumptions for each of the cost model are available in Appendix 3 – Market Analysis.

Table 14: Key Assumptions in each of the cost component

Cost Component	Key Steps	Key Assumptions		
		Parameter	Min	Max
Capital and Insurance Cost	• Capital Cost is the sum of depreciation cost and finance cost. Certification costs were included in aircraft price • Residual value of the aircraft was assumed to be negligible • Aircraft insurance is the sum of liability and hull insurance, calculated as % of aircraft price	*Vehicle life (flight hours)*	12k	15k
		Depreciation Rate (%)	5%	10%
		Finance Rate (%)	5%	10%
Energy and Battery Cost	• Energy required was calculated as the sum of energy required in each phase of the flight described in Section 10.1 • Battery pack sizing was done based on the longest mission and battery recycling was assumed to be negligible	*Battery Specific Energy in Wh/kg*	300	400
		Battery Capacity Specific Cost ($/kWh)	200	250
		Energy Conversion Efficiency (%)	90%	98%
Crew Cost	• Assumed one full time equivalent pilot per aircraft and one full time equivalent ground crew member in the initial years of service • Each crew member undergoes annual training	*Pilot Salary per year (U.S. $)*	50k	90k
		Ground Crew Salary per year (U.S. $)	20k	30k
Infrastructure Cost	• Calculated infrastructure cost by extrapolating car parking garage style architecture and construction to fit an aircraft • Same infrastructure was also used to park the aircraft overnight. A nightly parking fee was added	*Cost of one supercharger ($)*	200k	300k
		Cost of one regular charger ($)	10k	20k
Maintenance Cost	• Calculated based on per-mission basis by multiplying ratio of maintenance man hours to flight hours and mechanic wrap rate	*Mechanic Wrap Rate ($ per hour)*	$60	$100
		Maintenance man-hours per flight hour	0.25	1

It was observed that the median operating cost per passenger mile decreased as the vehicle's number of seats increased due to economies of scale for maintenance costs, indirect operating costs, and capital costs. Multirotor(s) were found to have high operating cost per passenger mile due to lower cruise speed compared to other types of eVTOLs. For further analysis, we used median values for each seat category as each vehicle type competed for the same air-taxi market and had to be priced similarly. Please see Appendix 3 – Market Analysis for breakdown of each cost component.

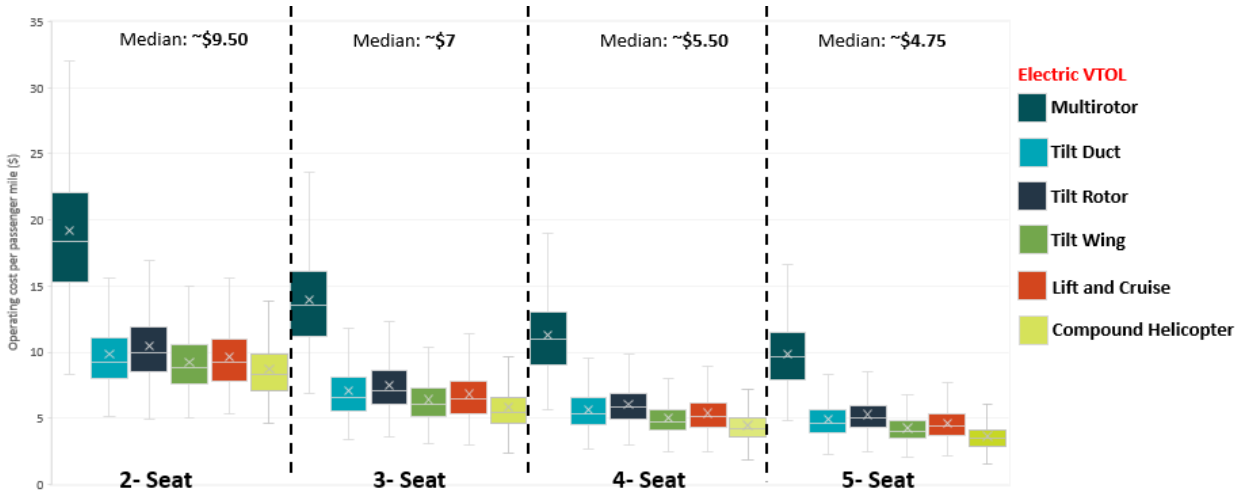


Figure 39: Operating cost per passenger mile

High degree of uncertainty in cost calculation was observed (shown by grey lines in Figure 39), which was largely driven by assumptions related to network efficiency (utilization, load factor, and dead-end trips %) and cruise speed. We noted in Figure 40: Importance of operating assumptions that higher the network efficiency (i.e., high utilization, high load factor, and low dead-end trips %) and cruise speed, lower the operating cost per passenger mile.

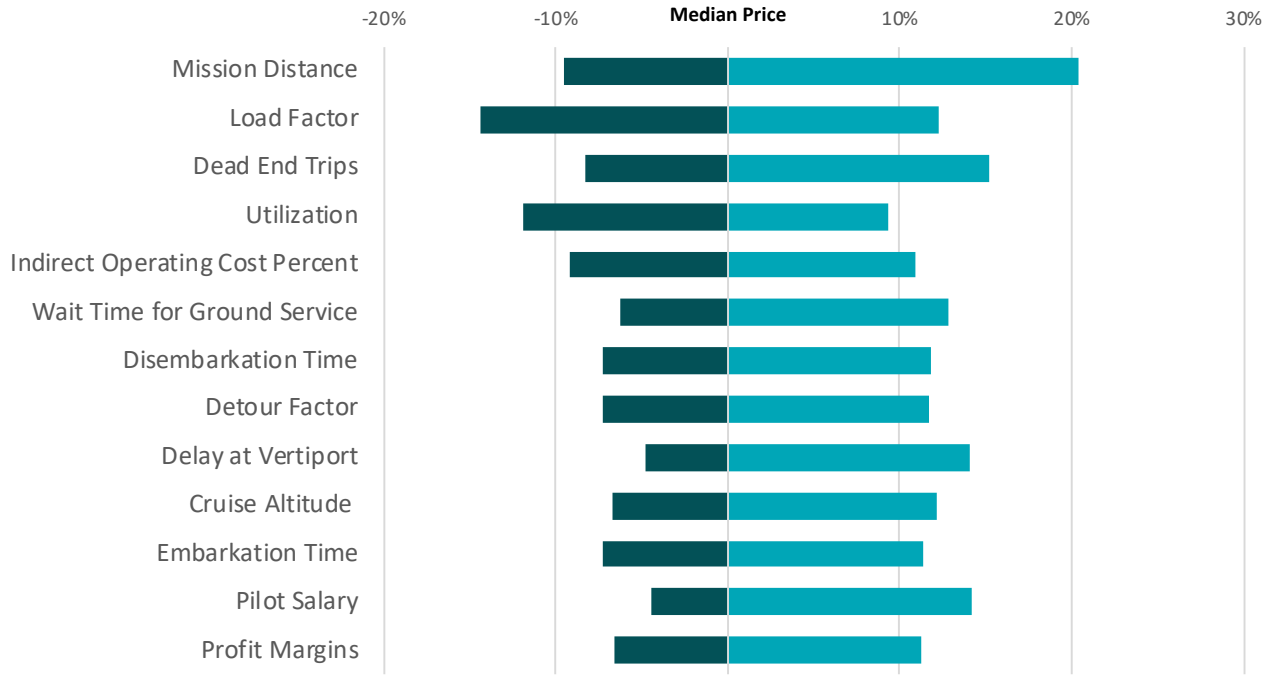


Figure 40: Importance of operating assumptions

Maintenance cost, Capital Cost, and Crew Cost represented ~60-70% of the overall operating cost. Most of the cost components on per passenger basis decreased for aircraft with a greater number of seats.

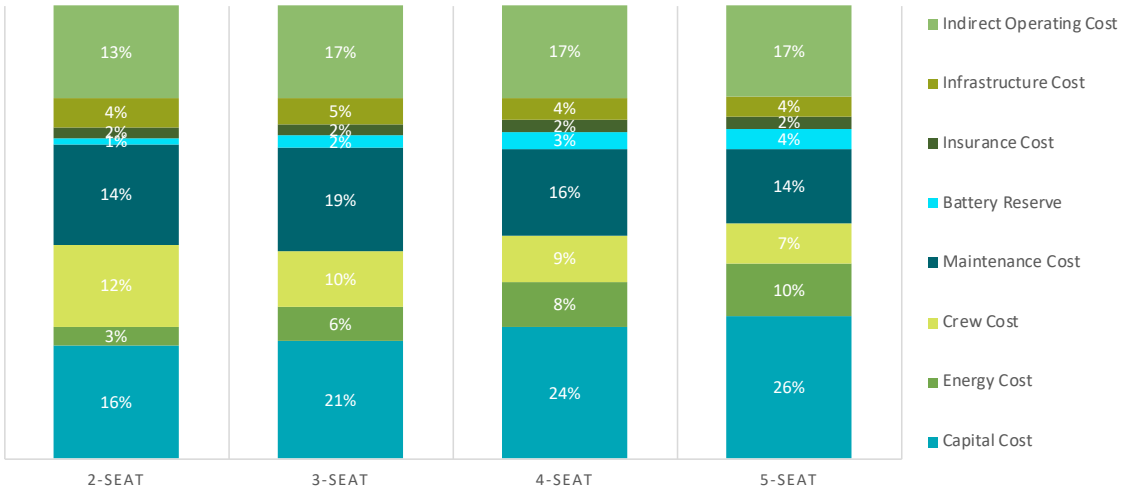


Figure 41: Operating cost breakdown

Operators are expected to use a variety of pricing strategies when selling air taxi services[65]. For this analysis, we used cost plus profit pricing strategy for the operators with an assumed profit margin of 10-30%. Finally, we assumed that the Air taxis and Airport Shuttle services will be subjected to taxes and fees like on demand taxis or ride sharing services. These taxes can range from sales tax, commercial motor tax, workers compensation fund, surcharge for public transportation, surcharge for accessibility, licensing fees, recall charges, inspection fees, environment tax, and local/state property tax. Each of these tax components depends on location and we assumed a unified tax rate of 5-15%.

We observed that a 5-Seat eVTOL is expected to cost around **$6.25 per passenger mile** in the near term with an uncertainty of +/-50%, which was lower than current operated helicopters[66] but higher than all the ground services. However, in the long term, with higher operational efficiency, technology improvement and autonomy can potentially reduce the cost by 60%.

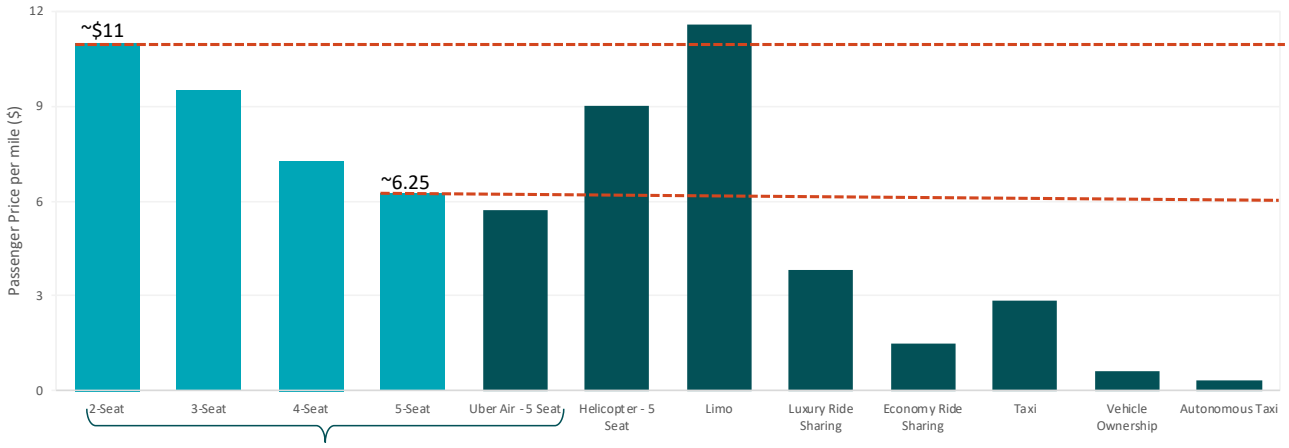


Figure 42: Price comparison with other modes of transportation

[65] Operators are expected to first price their services based on buyer's perceived value of the service followed by bundle pricing and other cost-based methods. In the longer term, operators might pursue competition-based pricing to compete with the strong competition from all forms of transportation.

[66] Helicopters were operated on the same mission as an eVTOL with same operating assumptions.

10.4 Market Size and Value

The Booz Allen team relied on first-principles approach to calculate market size and value of Airport Shuttle and Air Taxi Markets. As described in Figure 43, a demand modeling was performed using a five-step process, including Trip Generation, Scoping, Trip Distribution, Mode Choice, and downstream application of Constraints to evaluate their effect on market size and viability.

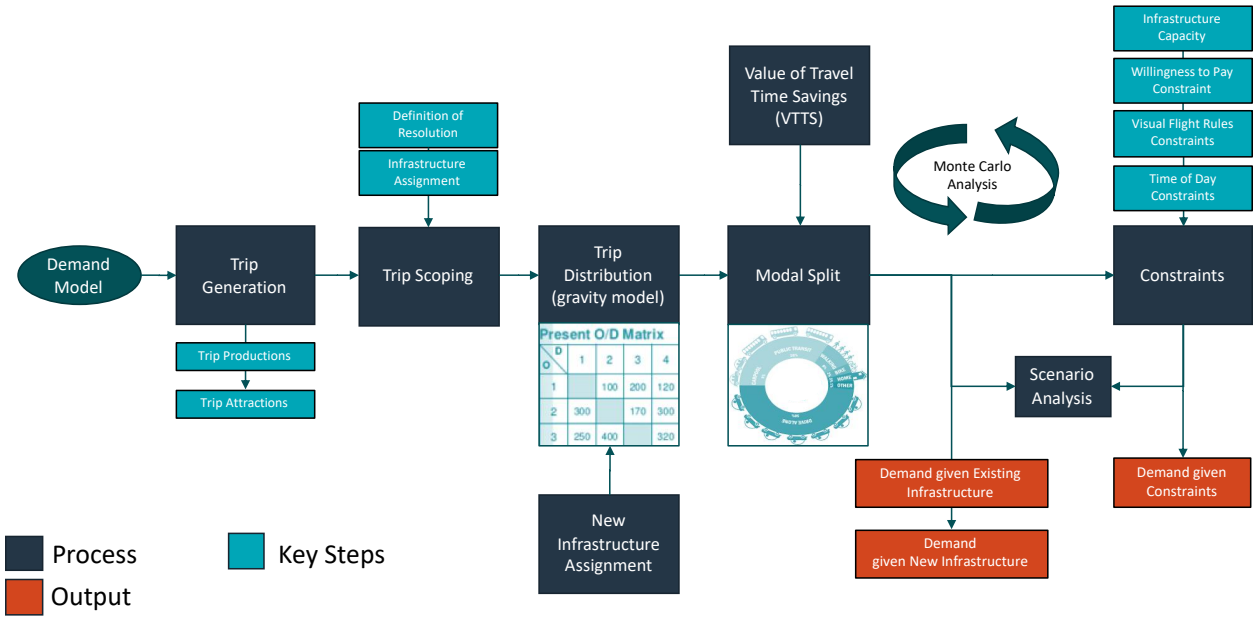


Figure 43: Structure of demand side model for urban air taxi

Step 1: Trip Generation is the first step in demand modeling and results in trip production and trip attractions. For this step the model was calibrated using the U.S. Department of Transportation (DOT) data that defines trips in two categories: mandatory trips (e.g., work trips) and discretional trips (e.g., shopping, entertainment, dinner, etc.). For air taxi market, works trips were generated using American Community Survey (ACS) commuting data shown in Figure 44 (5-year estimates, 2016) and discretional trips were generated using 2017's National Travel Household Survey (NTHS) data. For trips to or from U.S. airports, the U.S. Bureau of Transportation Statistics (BTS) T-100 Market (All Carriers) 2018 data was used. Airport specific trips were generated by proportionally distributing daily demand from each airport in an urban area to each census tract based on its population.

Figure 44: Total Daily trips in each urban area

Step 2: Trip Scoping – ACS datasets were available at different geographic levels (in the decreasing order of resolution), block groups, census tracts, place, county, and urban area for different mode types as shown in Figure 45. Temporal resolution of the datasets was limited to an average day of year (i.e., each weekday in a year was considered same). The team first chose few small urban areas like Phoenix, Denver, Miami, Dallas, and performed tradeoff analysis between fidelity in results and computational speed for different combinations of geographic levels and mode types. The analysis was then conducted at a census tract level for mode types classified as driving, ride-sharing, taxi, public transportation, and walking to achieve optimum fidelity in results and computational speed.

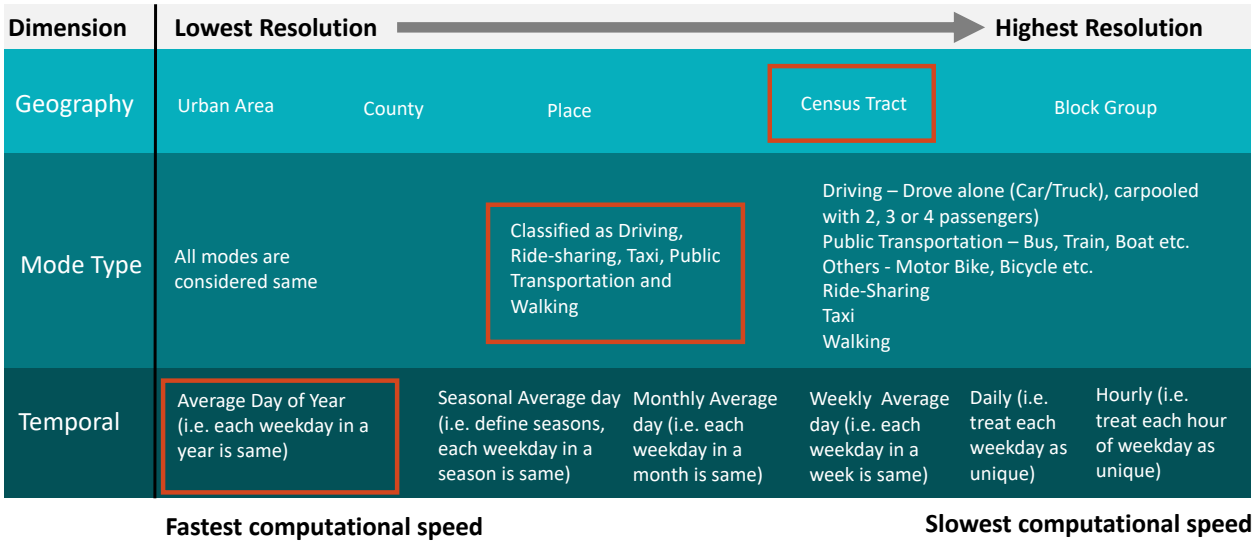


Figure 45: Tradeoff between fidelity in results and computational speed

Next, existing infrastructure (i.e., helipads, referred to as vertiports in the study) and airports (small or big) obtained from Federal Aviation Administration's (FAA) Aviation Environment Design Tool (AEDT) database were used for first few years of operations. This assumed that no new vertiports would be constructed before the UAM market emerges. The effect of capacity enhancements in the form of additional vertiports and increased capacity per vertiports were evaluated in the Monte Carlo based sensitivity analyses. Each infrastructure was assigned to each tract using a nearest neighbor algorithm. No two infrastructure were assigned to the same tract.

In parallel, for airport specific trips, due to technical feasibility and travel characteristics limitations, not all passengers arriving or departing at a major airport were expected to be potential customers of Airport Shuttle service. For example, it was considered unrealistic for a family of four traveling long distance with over 200 lbs. of baggage (due to vehicle performance limitations). Therefore, the demand was scoped to focus the airport shuttle analysis on 1 to 3 passengers per air ticket.

Step 3: Trip Distribution – Trips were distributed between census tracts (origin-destination pairs) using a simplified gravity model assuming equal likelihood of individual trip interchanges between the tracts. All the trips where UAM total travel time was more than the travel time for ground transportation were removed from further analysis.

Step 4: Mode Choice – Mode Choice Modeling was used to predict traveler mode choice while completing a certain trip. Air Taxi and Airport Shuttle service was made to compete with personal cars, taxi, ride-hailing service, and public transportation, among others. Next, a utility function was developed based on two key attributes that influence choice of mode, travel time, and travel cost per median household income per hour. Coefficients of the utility function was calibrated by fitting a logit model to the training data generated using the 2016 American Community Survey and General Population Survey described in societal barriers section.

Having calibrated the utility function, a probabilistic choice model, Multinomial Logit Model (MNL), was selected to describe preferences and choice of a user in terms of probabilities of choosing each alternative rather than predicting that an individual will choose a particular mode with certainty.

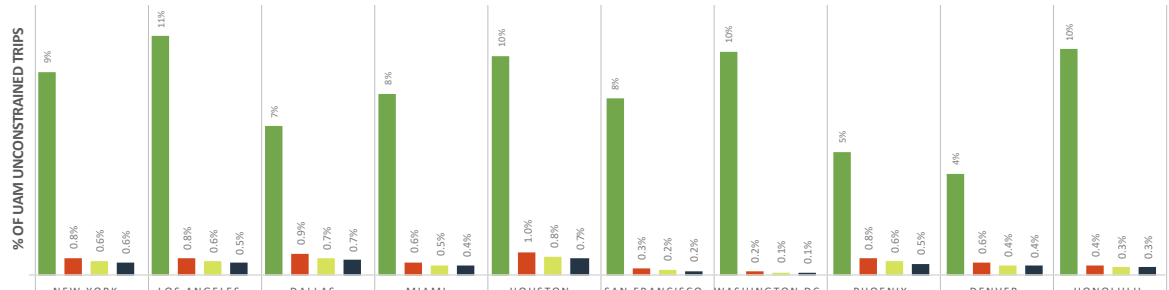
Step 5: Constraints – As a final step, demand generated in Step 4 was constrained by passenger's willingness to pay, infrastructure availability and capacity, time of day and visual flight rules operation restrictions. These constraints were applied sequentially as shown in Figure 46. See Appendix 3 – Market Analysis for more details in each constraint application.

Unconstrained Scenario	Refers to the best case scenario where infrastructure to take-off and land is available at every census tract and is not constrained by capacity; operations are unaffected by weather and can be conducted 24/7. Finally, demand was not constrained by willingness to pay (WTP) i.e., some passengers might still chose UAM service if the cost of service is more than WTP
Willingness to Pay (WTP) Constraint	Willingness to pay was calculated as passengers willingness to spend more based on travel time savings. This constraint restricts demand for cases where cost of UAM service was more than passengers WTP
Infrastructure Constraint Scenario	This scenario utilized existing infrastructure in the form of heliports and airports (assuming only one landing take-off pad)
Infrastructure Capacity Constraint	Refers to the demand reduction due to existing infrastructure's operational capacity on per hour basis
Time of Day Constraint	Demand reduction due to operations in specific time of day i.e. 7am-6pm that covers 80% of the demand and also has minimal impact on public (e.g. due to noise pollution)
Weather Constraint	Initial operations were expected to be under Visual Flight Rules (VFR) conditions

Figure 46: Step-by-Step Constraint application

Across the sample of ten urban areas considered in this analysis, air taxi and airport shuttle markets were found to be viable (see Figure 47 for details). However, it was observed that approximately 0.5% of unconstrained trips (air taxi and airport shuttle combined) were captured after applying all constraints considered in the base case scenario. Infrastructure constraints (i.e., number of vertiports and their capacity) were found to severely limit the potential demand for UAM. Finally, most of the available demand was captured by replacing mandatory trips on the ground with a trip time greater than 45 mins. No significant demand for discretional trips was found due to passenger's low willingness to pay[67]. This demand was mainly served by 4-seat and 5-seat eVTOLs.

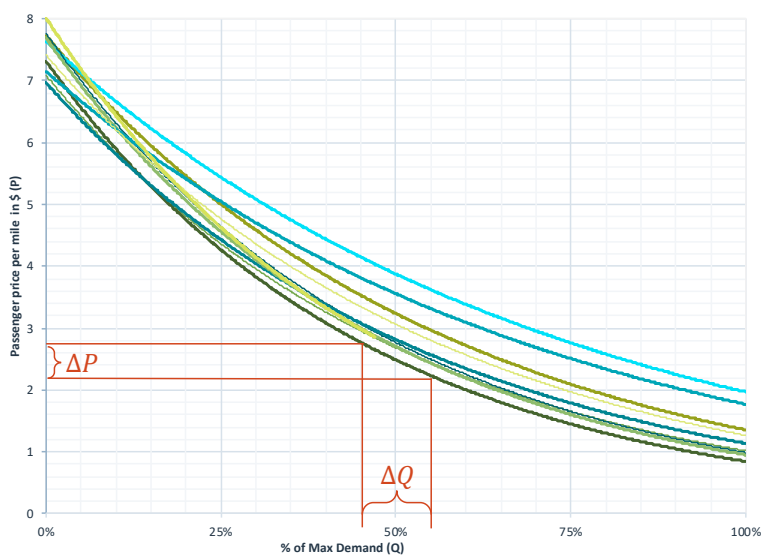
[67] U.S. Department of Transportation provides guidance on value of travel time savings (VTTS) for passengers on mandatory (i.e., work related) and discretional (i.e., personal) trips. In general, VTTS is estimated to be half for personal travel when compared to work related travels (i.e., a passenger on a personal trip would be willing to pay half as compared to work trip for same amount of travel time savings).



	NEW YORK	LOS ANGELES	DALLAS	MIAMI	HOUSTON	SAN FRANCISCO	WASHINGTON DC	PHOENIX	DENVER	HONOLULU
Un-constrained	1, 421, 000	1, 380, 000	717, 000	587, 000	673, 000	606, 000	600, 000	422, 000	358, 000	161, 000
Infrastructure Constrained	127, 000	145, 000	47, 000	47, 000	65, 000	47, 000	59, 000	23, 000	16, 000	16, 000
Capacity Constraint	11, 000	10, 500	6, 700	3, 400	7, 000	1, 800	1, 100	3, 200	2, 000	700
Time of Day Constraint	8, 800	8, 400	5, 360	2, 720	5, 600	1, 440	880	2, 560	1, 600	560
Weather Constraint	8, 000	7, 500	4, 750	2, 470	4, 890	1, 250	780	2, 230	1, 460	550

Figure 47: Base year Demand comparison for focus urban areas

The price elasticity of demand (PED) as shown in Figure 48 modeled the sensitivity of the demand to changes in the price. It was observed that the absolute value of PED was greater than 1 for all urban areas indicating elasticity in demand. Negative sign of PED indicated that the demand decreases with increase in price of the service. Some urban areas like Denver, Houston, and Honolulu were found to be more price sensitive than New York, Los Angeles, and Washington, D.C. Next, revenue for each P and corresponding Q was calculated by multiplying both the quantities together. It was observed that maximum revenue for each of the urban area was achieved at ~$2.50-$2.85 passenger price per mile.



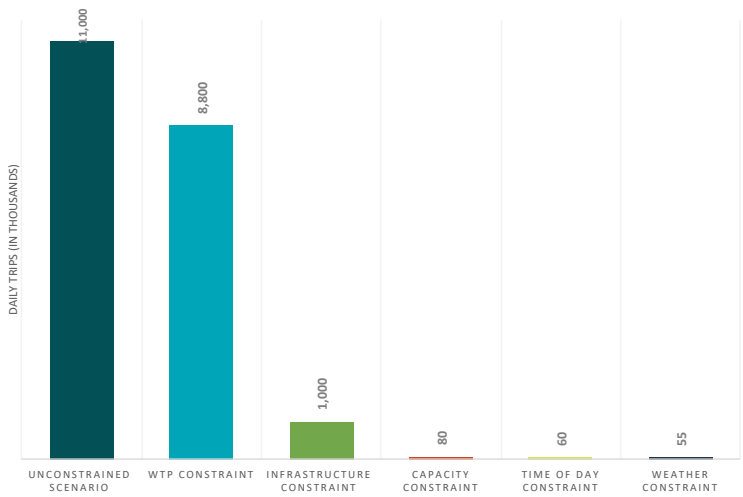
	PED	Passenger price per mile for Max. Revenue (R)
Dallas	-3.48	$2.84
Denver	-4.29	$2.69
Honolulu	-4.17	$2.82
Houston	-4.05	$2.83
Los Angeles	-3.36	$2.60
Miami	-3.85	$2.60
New York	-2.80	$2.63
Phoenix	-3.56	$2.50
San Francisco	-3.52	$2.70
Washington DC	-2.68	$2.78

Figure 48: Price elasticity demand curve and revenue maximization.

Total Market Size and Value: Total combined demand of Air Taxi and Airport Shuttle was then extrapolated to all the 484 urban areas in the U.S. on the basis of results from ten focus urban areas. ACS commuting datasets were available for each census tract within an urban area for different travel time ranges including: 0-10, 10-20, 20-30, 30-60, 60-90, and 90+ minutes. For each of this travel time range, percent trips captured by UAM service from ground transportation was calculated. It is to be noted that there was negligible demand found for mandatory trips completed in less than 30 minutes by ground transportation. Next, to

calculate demand for a particular travel time range, median percent capture rate was calculated across all the census tracts in all the focus urban areas and multiplied with total number of annual mandatory trips taken in the U.S. Finally, demand from different travel time ranges were aggregated to calculate total demand.

It was observed that, in the near term, the Air Taxi market and Airport Shuttle market has a combined potential demand of 55,000 daily trips (or 82,000 daily passengers), which represented 0.1% of total daily work trips taken across the U.S. This potential demand for UAM has an annual market value of $2.5 bn and could be served by approximately 4,000 aircraft, mainly comprising of 4-seat and 5-seat aircraft. However, under the best case (unconstrained) scenario, we observed a potential demand of 11 million daily trips (20% of all the daily work trips taken in the U.S.) at a market value of $500 billion.



	Daily Trips	Daily Passengers	Total Number of Aircraft	Annual Market Value (in bn $)
Un-constrained	11,000,000	16, 000, 000	850, 000	500
WTP Constraint	8, 800, 000	13, 000, 000	680, 000	400
Infrastructure Constrained	1, 000, 000	1, 500, 000	80, 000	45
Capacity Constraint	80, 000	120, 000	6, 000	3.6
Time of Day Constraint	60, 000	90, 000	4, 500	2.75
Weather Constraint	55, 000	82, 000	4, 100	2.5

Figure 49: Near-term Market Size and Value

10.5 Potential Externalities

Air taxi and Airport shuttle markets were expected to exhibit a wide range of impacts on current air traffic management, background noise and environment sustainability of transportation systems.

% population under Controlled Airspace					
Urban Area	**Class B**	**Class C**	**Class D**	**Class E**	**Total**
New York	41%	15%	3%	0%	60%
Los Angeles	3%	42%	17%	0%	62%
Dallas	23%	35%	0%	0%	58%
Miami	17%	39%	14%	0%	70%
Houston	30%	15%	0%	0%	45%
San Francisco	13%	24%	24%	0%	61%
Washington DC[1]	11%	4%	0%	0%	15%
Phoenix	19%	42%	0%	0%	61%
Denver	3%	36%	0%	0%	40%
Honolulu	22%	18%	5%	2%	47%

% Operations under controlled vs uncontrolled Airspace		
Urban Area	**Not Controlled Airspace**	**Controlled Airspace**
New York	10%	90%
Los Angeles	10%	90%
Dallas	15%	85%
Miami	5%	95%
Houston	16%	84%
San Francisco	12%	88%
Washington DC	22%	78%
Phoenix	13%	87%
Denver	36%	64%
Honolulu	11%	89%

[1] Washington DC is usually under security related TFR

Figure 50: Operations in Controlled vs Uncontrolled airspace

10.5.1 Air Traffic Management: To scope the potential effect of UAM on the Air Traffic Management (ATM) system and better understand where eVTOL may operate relative to types of airspace, a geospatial comparative analysis of UAM flight patterns and airspace types was conducted. More than 50% of the population in most urban areas were under controlled airspace which could limit the number of operations in an urban area. A first order assessment shows that more than 85% of the operations in most urban areas will be flown under controlled airspace as shown in Figure 65 above. Existing air traffic control may not have sufficient capacity to administer the large amount of operations. New technologies like UTM will be needed to serve the Air Taxi market.

10.5.2 Noise: National Park Service made long term measurements of sound in parks as well as urban and rural areas across the country which helped predict current sound levels for the entire United States. Using this information, average noise level around each existing infrastructure was calculated. We expected noise impacts to be more severe near the take-off and landing areas. Based on our first order analysis, we observed that in certain urban areas like New York, Denver, San Francisco, etc., large percentage of operations (using existing infrastructure) will be flown in area of low background noise levels[68]. Usually, community acceptance in areas of low background noise is low.

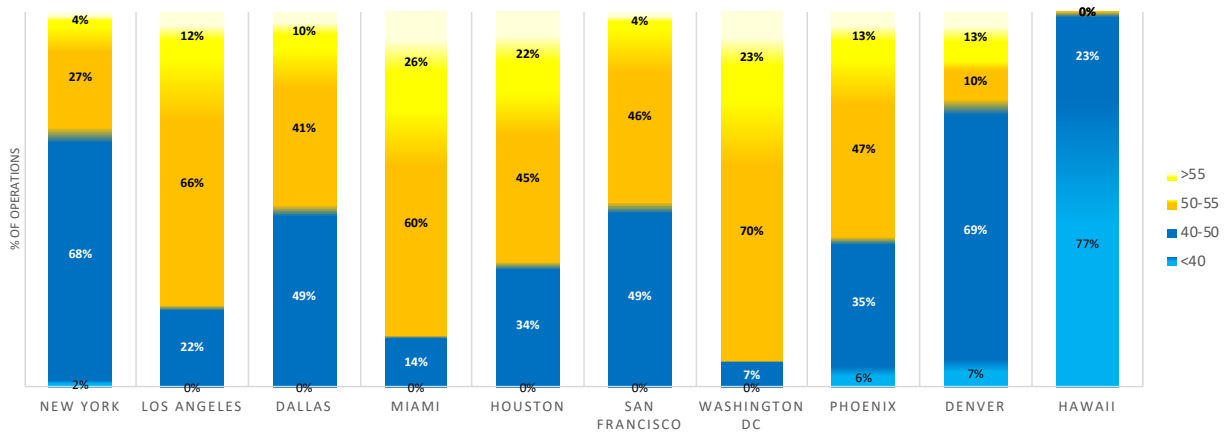


Figure 51: Percent of operations at different background noise levels

10.5.3 CO_2 emissions: Our first order analysis found that a 5-seat piloted eVTOL (at 75% load factor) was expected to generate 2 times more well-to-wake (WTW) CO_2 emissions per passenger mile[69] when compared to an all-electric car (e.g., Tesla Model S 75D, 1.54 persons per vehicle occupancy rate) as shown in Figure 52.

[68] Low background noise level area does not necessarily indicate residential areas. It simply means that the existing infrastructure used in this analysis was in the area of low background noise. Further analysis must be done to quantify noise impacts on public.

[69] Considers the extra distance required on road vs air. A factor of 1.42 was used. To calculate CO_2 emissions, we used energy requirement per vehicle mile calculated earlier in supply side modeling and extrapolated Tesla GHG emissions per mile to obtain grams CO_2 per vehicle mile. Load factor of 75% (including pilot) was then applied to eVTOLs to obtain grams CO_2 per passenger trip mile. Does not include energy required to perform reserve mission and dead-end trips. Energy usage varies by the vehicle type (e.g., Tilt Rotor vs. Compound Helicopter) shown as uncertainty in Figure 51. Emission numbers shown in Figure 52 are based on average electricity grid for U.S. However, sources of electricity vary region by region and must be taken into account for detailed analysis.

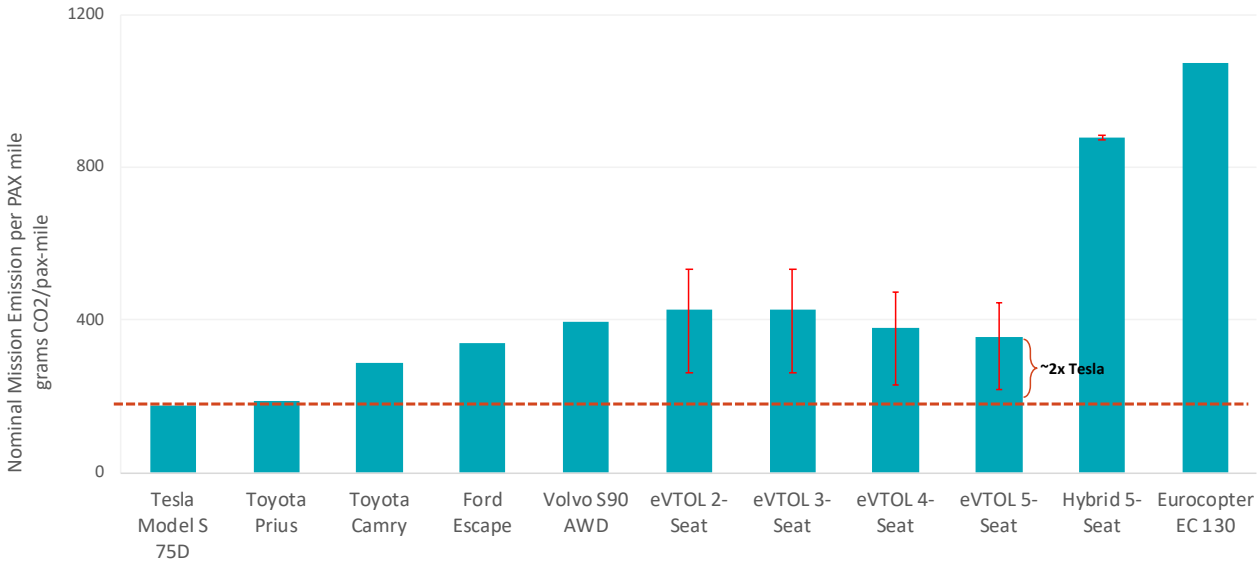


Figure 52: Well-to-wake greenhouse gas emissions comparison for eVTOLs

On average, Air Taxi and Airport Shuttle markets at the system level is likely to contribute significant more well-to-wake GHG emissions as compared to Tesla Model S 75D when the same Air Taxi mission is performed by Tesla on the ground.

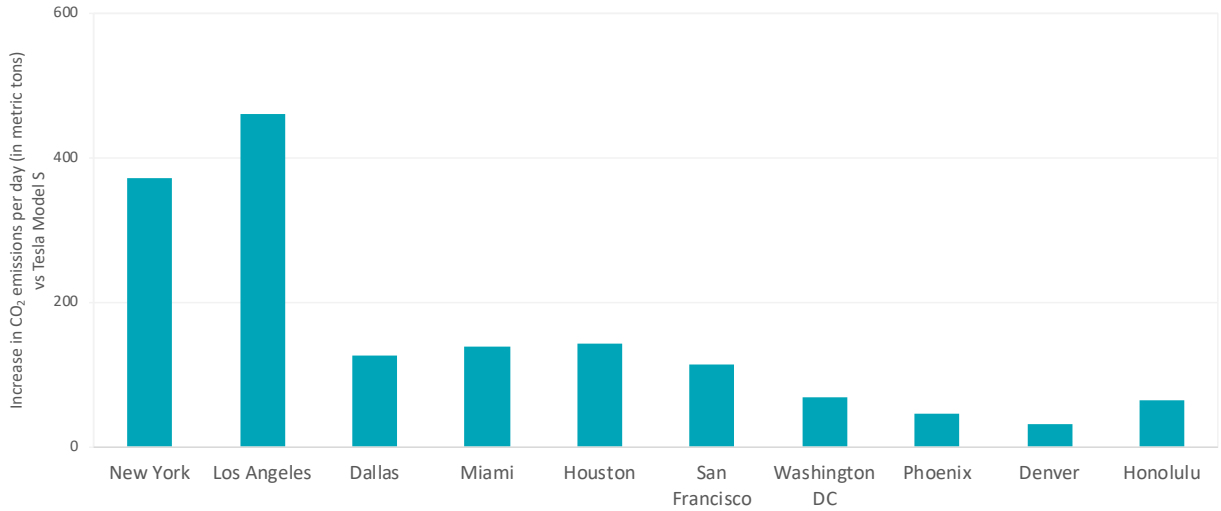


Figure 53: CO_2 emissions (well-to-wake) comparison of an eVTOL with Electric car

10.6 Scenarios

The emergence and growth of the Airport Shuttle and Air Taxi market is expected to be driven by several factors like ATM infrastructure capabilities and development, ground infrastructure capabilities, and development, aircraft noise/community noise tolerance, regulatory environment for certification, continued investment, and demand for taxi services. Therefore, our scenarios were dependent upon the current state of the UAT System of System (SoS) (e.g., in the analysis reference base year), decisions and actions by key stakeholders in the UAT market, future states (evolution) of the UAT System of System and emerging technologies.

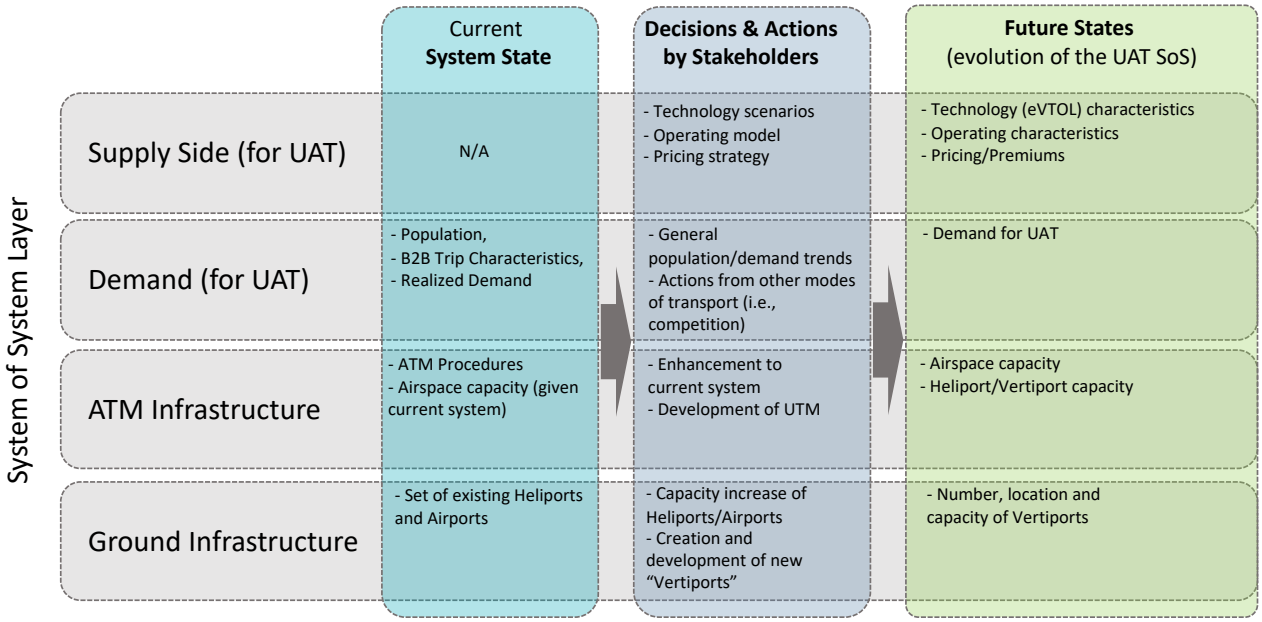


Figure 54: Framework for Scenario development.

A. Technology and Infrastructure Scenario

Technology Improvements: Improvements in battery technology and reduction of vehicle cost due to manufacturing learning and experience.

- Li-ion battery capacity specific cost is expected to fall to $100-150/kWh price range by 2025 at a $10/kWh annual reduction (Source: Nykvist)
- On average, vehicle cost reduces by ~15% on doubling the production (source: NASA). We double the production every five years

B. High Network Efficiency

Network efficiency parameters like load factor, utilization and dead-end trips were among the most significant parameters that influences the operating cost. We considered following improvements in these factors:

- Utilization: ~7 hours/day (from ~4 hours/day) may be possible due to supercharging, higher system capacity, demand etc.
- Load Factor: ~80% (from ~65%) similar to commercial aviation
- Deadend trips: ~20% (from ~37.5%)

C. Autonomous eVTOL

Most of the vehicles being developed are expected to have the capability to be fully autonomous. Given the pilot shortages facing the aviation industry and the scale of UAM operations anticipated, autonomy may play a key role to fully capture the realized demand. For this scenario we assumed the following:

- Pilot not required, and therefore all the seats were made available to passengers
- An extra ground staff was required to do safety briefings, loading and unloading of passengers

D. Infrastructure Improvements

This scenario assumed enhancement to the current air traffic system (e.g., following the development of a UTM system), which allowed in-part an increase of vertiport's operations capacity. Increase in number of vertiports was coupled with increase in capacity. We doubled the number of vertiports and operational capacity every five years to model new demand.

E. New importance of travel time

Continuous advancement in Virtual Reality / Augmented Reality, large screens, new interiors in ground vehicles and other teleconferencing technologies may enhance the productivity of the human driver/passenger while in transit. Increased productivity may result in decrease in value of travel time, thereby affecting demand of Urban Air Taxis. We evaluated the importance of travel time/cost by introducing a significance factor in the utility function and varied it between 0 and 1. '0' represents no importance to travel time and the user was expected to choose the mode entirely based on price, comfort, etc.

F. Competition with other modes

Autonomous cars, high speed rails, and many new or improved existing modes of transportation may pose a potential challenge to the adoption / demand of urban air taxis. Under this scenario, we examined the emergence of fully autonomous vehicles (AVs) only. BCG's U.S. Self-Driving Cars survey 2014 showed strong willingness among the American consumers to buy autonomous cars. The analysis further showed a penetration rate of 0.5% and 10% in 2025 and 2035 for full AVs. At an average occupancy rate of ~65% (similar to eVTOL), we used ~$0.9 cost per passenger mile, which was ~35% less than current car ownership / operating costs in our mode choice model.

G. Telecommuting

Regular telecommuting grew 115% in the past decade (i.e., ~10% annual), nearly 10 times faster than the rest of the workforce. Current telecommuting population of 3.9 million (3% of total workforce) avoided 530 million trips or 7.8 vehicle miles annually (source: Global Workforce Analytics). We considered a scenario where telecommuting continues to increase at a rate of ~10% every year to scope the available demand.

H. Congestion and Latent Demand

eVTOLs can induce new mobility patterns including de-urbanization (i.e., people moving out of the city due to faster transportation options available). We explored such a scenario using parametric analysis by varying average distances for each trip by -25% to +25% at an interval of 10%. Negative percentage indicates increased urbanization. Finally, mega cities can get more congested over time. However, in some scenarios (more pooling, better public transportation, etc.), cities can also de-congest. We explore such possibilities by varying average driving speed by -25% to 25% at an interval of 10%. Negative percent indicates increased congestion.

Observation: Figure 55 shows relative demand curve (i.e., relative increase or decrease in demand due to change in scenario assumptions) for air taxi and airport shuttle service tested under decoupled scenarios A-H and a subset of coupled scenarios. We observed that autonomous cars and reduced importance of travel time will severely constrain the demand for Airport Shuttle and Air Taxi markets. Telecommuting, decongestion, and increased urbanization will further reduce the demand. On the other hand, high network efficiency, increased importance of travel time, autonomous eVTOL, technology improvements, congestion, de-congestion, and increased available infrastructure/capacity will all increase demand.

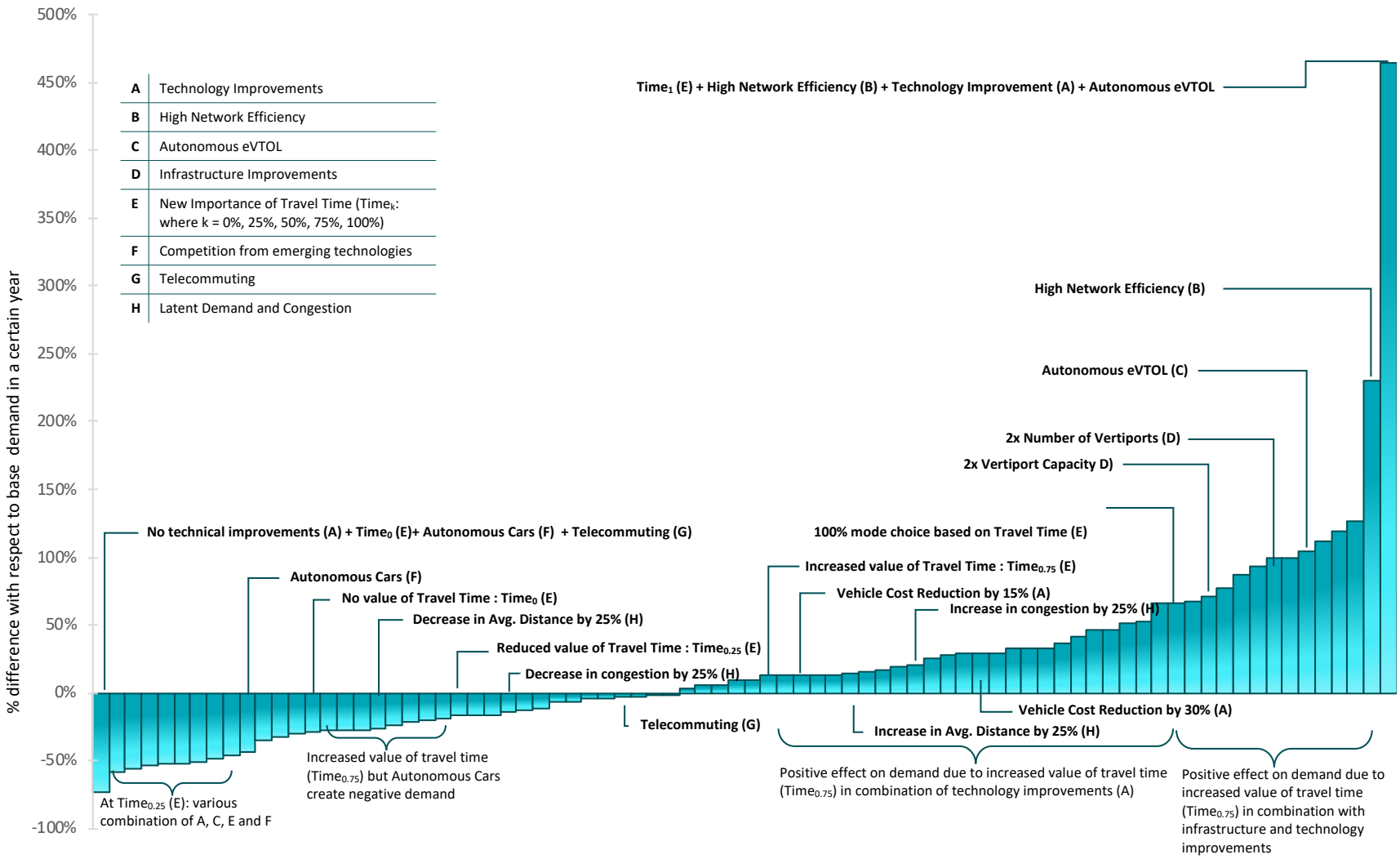


Figure 55: Air Taxi and Airport Shuttle demand curve

10.7 Airport Shuttle and Air Taxi Analysis Summary

Key Findings	Key findings uncovered during the market study of Airport Shuttle and Air Taxi use cases include: • High variability in demand is observed for all ten selected urban areas. Monte Carlo simulations provided a combined daily potential demand of ~55k daily trips (or ~ 80k daily passengers) across the U.S. that can be served by ~4k aircraft. • For the first few years of operation, market value of total available demand is projected to be ~$500 bn while only ~$2.5 bn can be potentially captured due to operation constraints. • In order to scale up demand, new ground infrastructure with larger operational capacity would need to be built, and operating costs lowered. Increased demand would risk posing greater noise concern for impacted communities. • Air Taxi market generates ~98% of its demand by capturing part of the long trips (i.e. 30 mins and more) served by ground transportation. • Over 85% operations may be flown in controlled airspace (B-E) where existing air traffic control may not have sufficient capacity to administer the large amount of operations. New technologies like UTM may be needed to serve the Air Taxi market. • Large percentage of air taxi operations are in the areas of low background noise. Community acceptance of operations in areas of low background is usually low. • On average, Air Taxi market is likely to add significant upstream GHG emissions as compared to high-end electric car when the same Air Taxi mission is performed by the electric car on the ground. • High operational efficiency (i.e., increased utilization, high load factor and lower dead-end trips), increased importance of travel time, higher congestion, autonomous eVTOL, technology improvements and increased available infrastructure/capacity may all increase demand. • Autonomous vehicle and reduced importance of travel time may severely constrain the demand for Air Taxis. Telecommuting further reduces the demand marginally.

11.0 AIR AMBULANCE

The Air Ambulance market includes travel to/from the hospital for emergencies and potentially hospital visits. The Booz Allen team selected this market as it is a complex market in terms of technical capabilities needed on board the aircraft, in addition to other legal and regulatory barriers. Also, Air Ambulances were expected to have higher public acceptability than airport shuttle and air taxi.

The Ambulance industry provides transportation of patients by ground or air, along with medical care. These services are often provided during a medical emergency, but they are not restricted to such instances. The vehicles equipped with lifesaving equipment operated by medically trained personnel in the U.S. can be broadly classified under:

- **Ground Transportation** – Typically used for short-distance patient transport from scene to hospital or inter-facility transfer. According to Ibis 2016, there are approximately 50,000 vehicles
- **Helicopter (or Rotary Wing)** – Used for short- distance air transport between the accident or patient site, and a hospital. According to Atlas 2017, there are 1049 helicopters
- **Fixed Wing Airplanes** – Typically used for long distance care and often utilized by patients that require transport across countries and oceans. According to Atlas 2017, there are 362 airplanes

The team investigated nine ambulance service levels as defined by Centers for Medicare and Medicaid Services (CMS) as shown in Table 15. CMS administers the Medicare program in the U.S. and works in partnership with state governments to administer Medicaid, the Children's Health Insurance Program (CHIP), and health insurance portability standards. Each service level had different medical equipment, crew (as shown in Table 16), vehicle requirements and were either served by ground transportation or air transportation depending upon the local 911 or equivalent service dispatch protocol.

Table 15: Different Service Level as defined by CMS

	CMS Service Level	Definition
Ground Ambulance	BLS (Basic Life Support) non-emergent	Provision of medically necessary supplies and services
	BLS Emergency	Provision of BLS services, as specified above, in the context of an emergency response
	ALS (Advanced Life Support) non-emergent	Provision of medically necessary supplies and services including the provision of an ALS assessment or at least one ALS intervention
	ALS1 (Advanced Life Support) emergent	Provision of ALS services in the context of an emergency response
	ALS2 (3 separate medications by IV)	Provision of ALS services in the context of an emergency response plus 3 separate medications by IV
	SCT (Specialty Care Transport)	Interfacility transportation of a critically injured or ill beneficiary including the provision of medically necessary supplies and services
	PI (Paramedic Intercept)	ALS services provided by an entity that does not provide the ambulance transport
Air Ambulance	Rotary Wing (Helicopters)	BLS or ALS type service for short distances that require rapid air transport
	Fixed Wing	BLS or ALS type service for long distances that require rapid inter-city air transport

Table 16: Crew Service Requirements

CMS Service Level	Driver[1]/Pilot[2]	Emergency Medical Technician (EMT)[3]	Paramedic[4]	Health Professional[5]	Total
BLS (Basic Life Support) non-emergent	1	2	-	-	3
BLS Emergency	1	2	-	-	3
ALS (Advanced Life Support) non-emergent	1	1	1	-	3
ALS1 (Advanced Life Support) emergent	1	1	1	-	3
ALS2 (3 separate medications by IV)	1	1	1	-	3
SCT (Specialty Care Transport)	1	1	-	1+	3+
PI (Paramedic Intercept)	1	1	-	1+	3+
Rotary Wing (Helicopters)	1	1	1	-	3
Fixed Wing	1+	1+	-	1+	3+

[1]**Driver**: Drives the patients from place to place. This analysis did not require driver to perform any medical duties.

[2]**Pilot**: Required to conduct flight planning, preflight risk analyses, safety briefings for medical personnel, and the establishment of operations control centers (OCC) for certain operators to help with risk management and flight monitoring.

[3]**EMT**: Entry-level EMS healthcare professional trained in BLS, anatomy/physiology, pathophysiology, pharmacology, ECG monitoring, advanced airway management (supraglottic airways) and spinal immobilization.

[4]**Paramedic**: Emergency Ambulance Practitioner. Trained in advanced Pharmacology, advanced Airway management etc., Advanced Life support.

[5]**Health Professional**: Trained to Paramedic level plus IV & IO access, a wide range of medications, tracheal intubation, manual defibulator, etc.

Based on National EMS Information System (NEMSIS) 2018 and the National Association of State EMS Officials (NASEMSO) 2011, there are 36 million events served by ambulance annually of which Rotary Wing (RW) and Fixed Wing (FW) comprise a relatively small proportion. 2/3rd of the RW operations are performed by life guard.

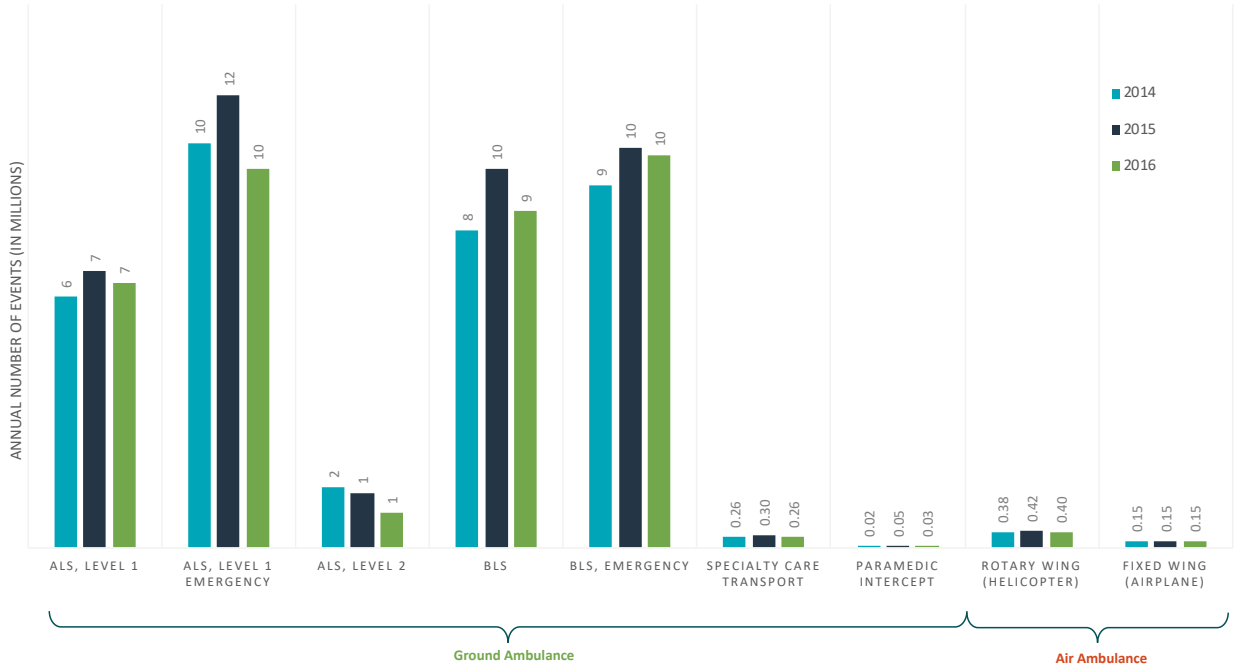


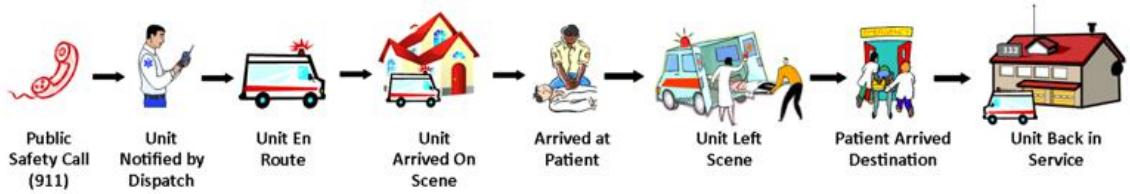
Figure 56: Annual events by CMS Service Level

11.1 Ambulance Mission and Scoping

The Booz Allen team first investigated an average ambulance mission by CMS service level. Each mission, regardless of service level, comprised of the following major steps:

- **Dispatch** - Time interval from Call Received to the Unit Notified by Dispatch
- **Chute** - Time interval from Unit Notified by Dispatch to Unit en route
- **Scene Response** - Time interval from Unit en route to Unit Arrived on Scene
- **Total Scene** - Time interval from Unit Arrived on Scene to Unit Left Scene
- **Transport** - Time interval from Unit Left Scene to Patient Arrived at Destination
- **Return** - Time interval from Unit left the Destination to Unit Back in Service

Total time interval from unit notified by Dispatch to Unit Back in Service was referred to as total call time and total time interval from unit notified by Dispatch to Transport of the patient to the nearest hospital was referred to as total transport time. Value proposition of introducing new vehicle types was to decrease total transport time of the patient. However, Dispatch, Chute, and Total Scene time were identified as fixed time interval that were unaffected by vehicle capabilities for individual service levels. Only Scene Response, Transport, and Return time intervals can be improved using faster vehicles.



	Dispatch	Chute	Scene Response	Total Scene	Transport	Return	Total Call time (in mins)
BLS	10	5	19	23	23	16	80
BLS Emergency	3	2	8	17	15	10	50
ALS	3	2	9	18	20	16	70
ALS1	2	2	8	17	17	18	60
ALS2	3	2	9	21	19	19	70
SCT	10	8	28	37	40	28	140
PI	3	3	10	13	18	27	70
Rotary Wing	5	11	18	32	28	37	130
Fixed Wing	9	17	32	53	61	54	220

Figure 57: Typical Ambulance mission as defined by NEMSIS 2018

For this analysis, we introduced vehicles with vertical take-off landing (VTOL) capabilities in electric and hybrid powertrain (referred to as hybrids in the study) categories. Like airport shuttle and air taxi markets, different vehicle types were considered. Based on the literature review, we assumed an average cruise speed of 250 mph for hybrid vehicle types in comparison to 150 mph for eVTOLs and 100 mph for conventional Helicopters (or Rotary Wing). First order analysis shows that the total transport time for ground transportation was faster for distances less than 20-25 miles than eVTOLs as shown in Figure 58. Also, we observed that an air ambulance is generally more expensive than ground ambulances. Therefore, we conclude that eVTOLs may not compete with ground ambulances at all in the first few years of entry into market. On the other hand, hybrids may compete for market share with ground ambulances for distances between 15-20 miles.

Next, we evaluated eVTOLs and hybrids competition to fixed wing (FW) market. Due to high range requirements of FW market, both eVTOLs and Hybrids were found to be not suitable to serve fixed wing market in the near term. It is to be noted from Figure 58 that hybrids could potentially serve Specialty Care Transport (SCT) service level. However, SCT is <1% of ambulance market and requires much larger vehicle size (higher number of crew). Therefore, we concluded that eVTOL and hybrids will only compete with rotary wing market in the near-term.

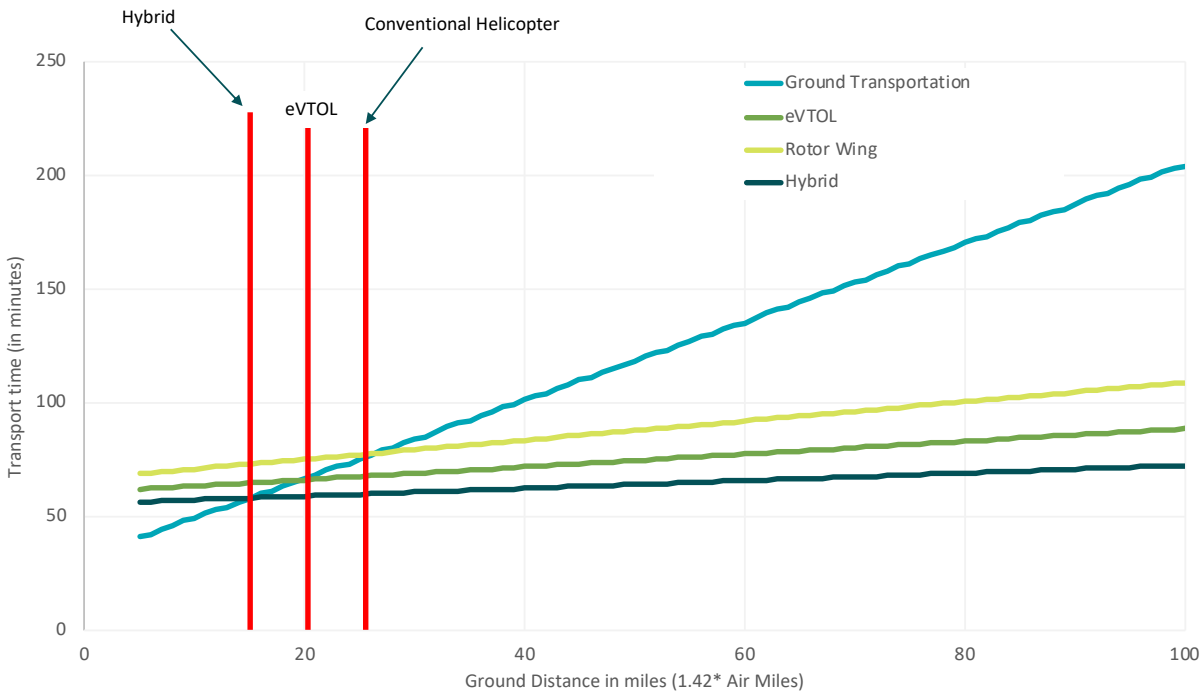
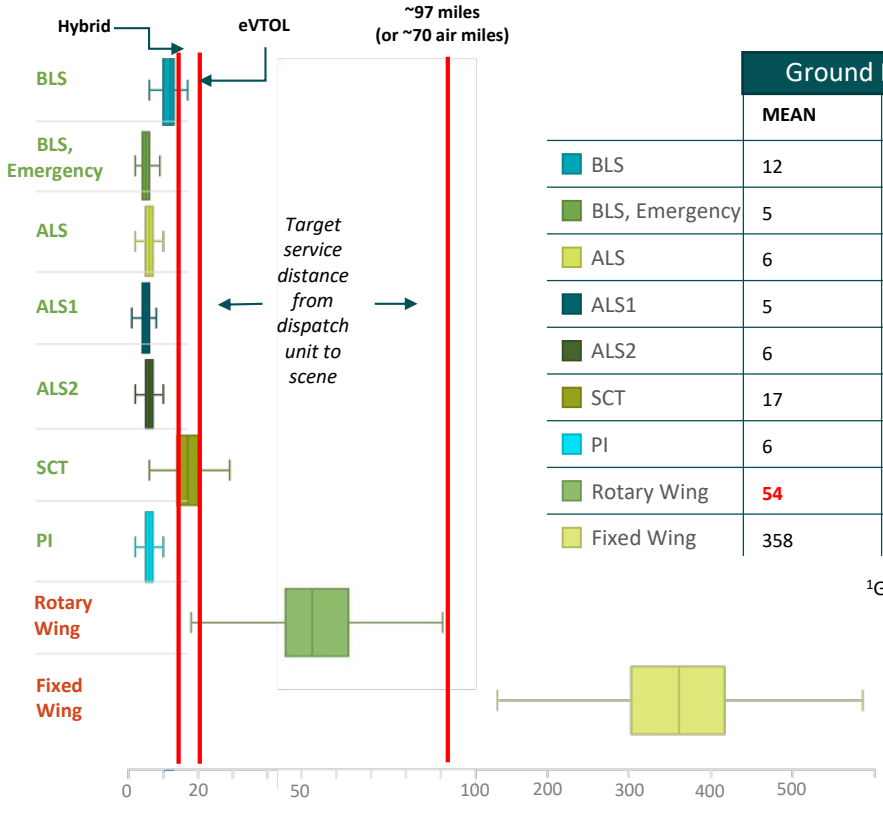


Figure 58: Competition with Ground Ambulances



	Ground Distance[1] (in miles)		
	MEAN	MIN	MAX
BLS	12	4	21
BLS, Emergency	5	2	9
ALS	6	2	11
ALS1	5	1	8
ALS2	6	2	10
SCT	17	6	31
PI	6	2	12
Rotary Wing	54	17	97
Fixed Wing	358	97	616

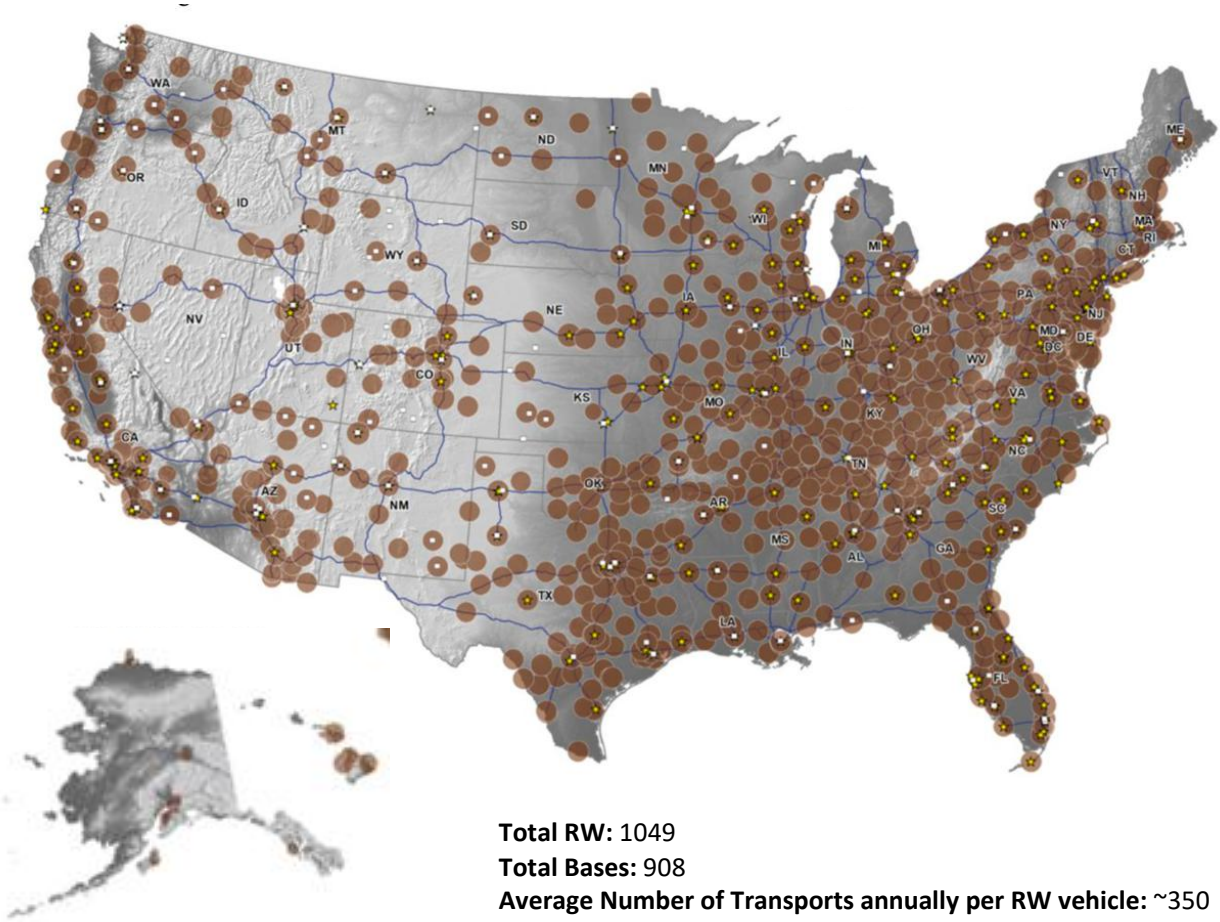
[1]Ground Miles = 1.42* Air Miles

Figure 59: Ground distance for different service levels from dispatch to scene

11.2 Current Rotary Wing Market

As per Atlas & Database of Air Medical Services (ADAMS)[70], there are currently 1049 rotary wing (RW) air ambulances operated from 908 bases across the U.S. as shown in Figure 60. Brown circles indicate 10-minute fly circles around each base where a RW is stationed. 84.3% of the population is covered within a 20 min response time (RW launch time + 10 min flight time).

Historical data suggested that both aircraft and bases steadily increased from 2005 to 2015. While bases continue to show a roughly linear increase, the number of RW aircraft for the year 2015-2017 seemed to plateau (or reached maturity) due to consolidation of providers[71] and uncertainty created due to certain legislative changes[72].



Total RW: 1049
Total Bases: 908
Average Number of Transports annually per RW vehicle: ~350

Figure 60: Rotary Wing and Air Ambulance Bases in U.S.

[70] ADAMS, 2017. Available at http://aams.org/. Last visit – November 14, 2018.

[71] In 2011, Air Methods acquired Omniflight Helicopters, a provider of air medical transportation services in 18 states, while in 2016, Air Methods acquired Tri-State Care Flight, a provider of air medical transportation services in Arizona, New Mexico, Nevada, and Colorado.

[72] In 2015, a Legislation was introduced in House and Senate to increase Medicare payments for air ambulance providers and create a data-reporting program (supported by Association of Air Medical Services). In 2014, FAA amended regulation of air ambulances to have stricter flight rules and procedures and additional on-board safety and communication equipment, such as Helicopter Terrain Awareness and Warning Systems (HTAWS) and flight data monitoring systems within for years. Finally, in April 2015, Air ambulance pilots given more discretion when flying in bad weather conditions.

11.3 Air Ambulance Mission and Assumptions

A typical air ambulance mission consisted of three sub-missions as shown in Figure 61: Response (A-F), Transport (H-M), and Return to Service (N-R). We assumed that each of these sub-missions are flown at similar speeds and follow similar profiles (i.e., Taxi, Hover Climb, Climb, Cruise, Descend, Hover Descend, and Taxi). For the fourth mission (Scene) we assumed an air ambulance in Taxi mode. Total Flight time was the sum of response, transport, and return time. After completing the patient transport to the hospital, the air ambulance returned to its base (N-R) and was prepared for return to service (R-Q). For RWs, return to service time (referred to as preparation time) included the time to re-fuel the aircraft, which was assumed to be 5-15 mins while for eVTOL R_Q refers to the time required to recharge batteries for the next mission. Each flight sub-mission followed the same mission profile as Air Taxi and Airport Shuttle mission types. For hybrid aircraft, take-off landing is flown on electric (battery) power while rest of the phases are flown on turboshaft (source: XTI Aircraft).

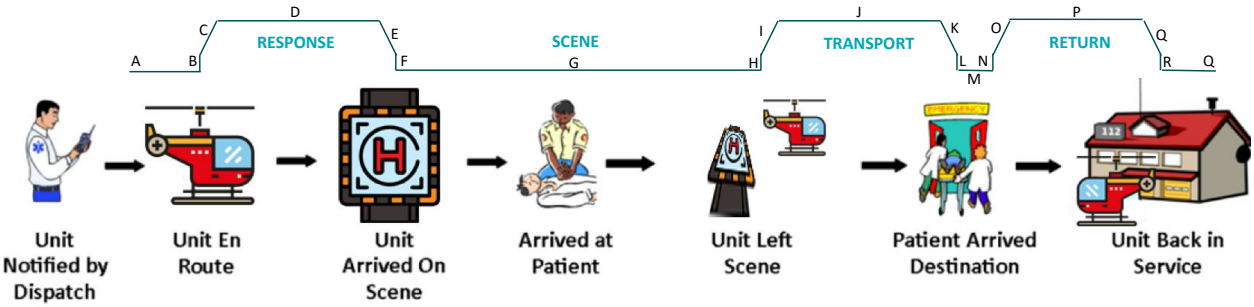


Figure 61: Typical Air Ambulance mission

Our team sized eVTOL and Hybrid aircraft for 1-patient emergency medical transports, both from accident scenes and between hospitals. Therefore, we considered a 5-8 seat size equivalent eVTOL and hybrid aircraft that can fly a cruise altitude of 500 to 5000 ft. As per FAA duty hour requirements, a single emergency eVTOL and hybrid was required to have 4 full time pilots, 4 full time flight nurses, and 4 full time paramedics with Commission on Accreditation of Medical Transport Systems (CAMTS) Accreditation. Each crew was required to go through annual training. All vehicle related assumptions like vehicle life and cost, insurance, power requirements, and energy cost, etc. were considered similar to airport shuttle and air taxi and simply extrapolated wherever relevant.

Table 17: Operations Related Assumptions for Monte-Carlo (first few years of service).

Parameter	Minimum	Maximum
Cruise Speed (for eVTOL)	125 mph	175 mph
Cruise Speed (for Hybrid)	200 mph	300 mph
Equivalent Number of Seats	5	8
Reserve (mins)	20	30
Range (miles)	50 + Reserve	200 + Reserve
Battery Capacity (kWh)	100	150
Battery Charger Power Setting (kW)	100	150
Annual number of Transports	300	400
Pilot Salary ($ per year)	$ 60,000	$ 100,000
Paramedic ($ per year)	$ 50,000	$ 75,000
EMT ($ per year)	$ 60,000	$ 90,000
Mechanic Salary ($ per year)	$ 50,000	$ 90,000

11.4 Cost per Transport

Similar to the Air Taxi and Airport Shuttle markets, we analyzed the technical feasibility of using nine type of VTOL vehicles as shown in Table 18. Only electric and hybrid version of tilt rotor and tilt wing were found to be suitable due to high range requirements. We followed a similar process as described in Section 11 to develop the reference vehicles, which were operated on a randomly generated air ambulance mission typically performed by RWs.

Table 18: Specifications of vehicles analyzed

	Classification	MIN CRUISE SPEED (mph)	MAX CRUISE SPEED (mph)	MIN RANGE (miles)	MAX RANGE (miles)
Electric	Multirotor	40	60	30	50
	Tilt Rotor	110	190	90	150
	Lift and Cruise	110	190	50	80
	Tilt Wing*	110	190	170	290
	Tilt duct	110	190	110	180
	Compound Helicopter	110	190	90	150
Hybrid	Multirotor	40	60	50	80
	Tilt Rotor*	200	300	Same as Helicopter	
Conv.	Multirotor	40	60	70	110
	Helicopter*	80	130	330	550

**Selected for analysis*

Next, the cost per transport for each vehicle type was calculated as a sum of its direct operating cost and indirect operating cost. The direct operating cost (DOC) included capital, energy, battery, crew, maintenance, and insurance costs, while indirect operating cost (IOC) was considered as percent of DOC. This percent was assumed to be 10-30%. Each of the cost component of direct operating cost was individually modeled as detailed in Figure 62. To conduct the sensitivity/Monte Carlo analysis, 10,000 randomly generated iterations were performed.

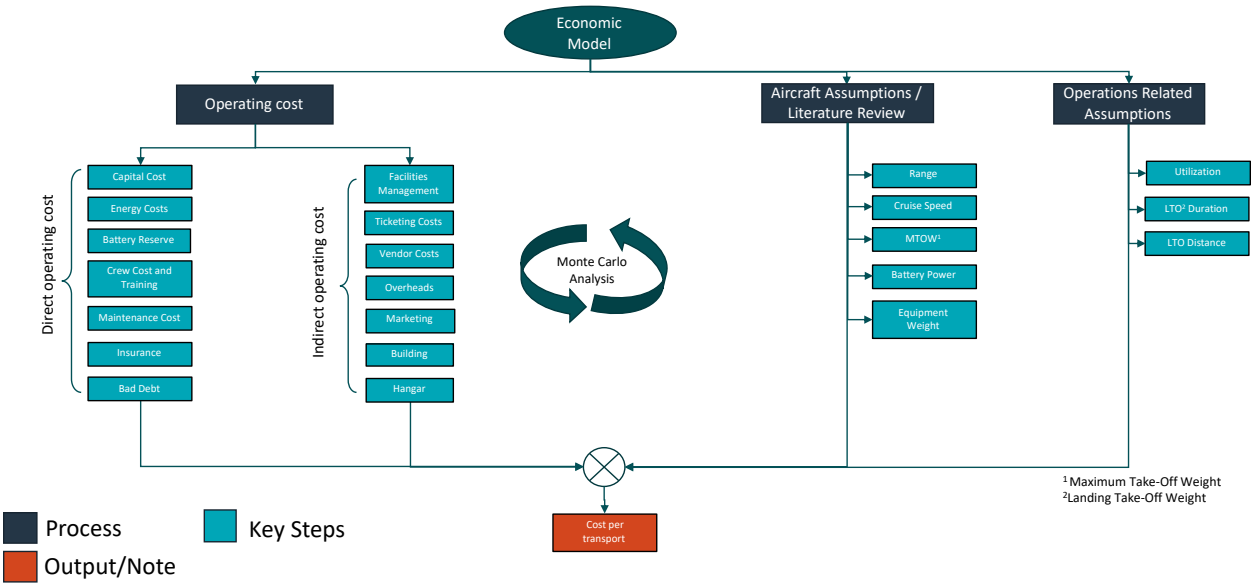


Figure 62: Structure of supply economic model for Air Ambulance

It was observed that the median cost of operating an eVTOL air ambulance was approximately $9,000 per transport and hybrid air ambulance was around $9,800 per transport as compared to $10,000 per transport

for rotary wing helicopter [AAMS 2017] and $500 per transport for ground ambulance. High degree of uncertainty was observed, which was mainly driven by assumptions on payroll and number of transports. We concluded that eVTOLs and hybrid aircraft were not necessarily the more cost-effective option when operated similar on RW business models.

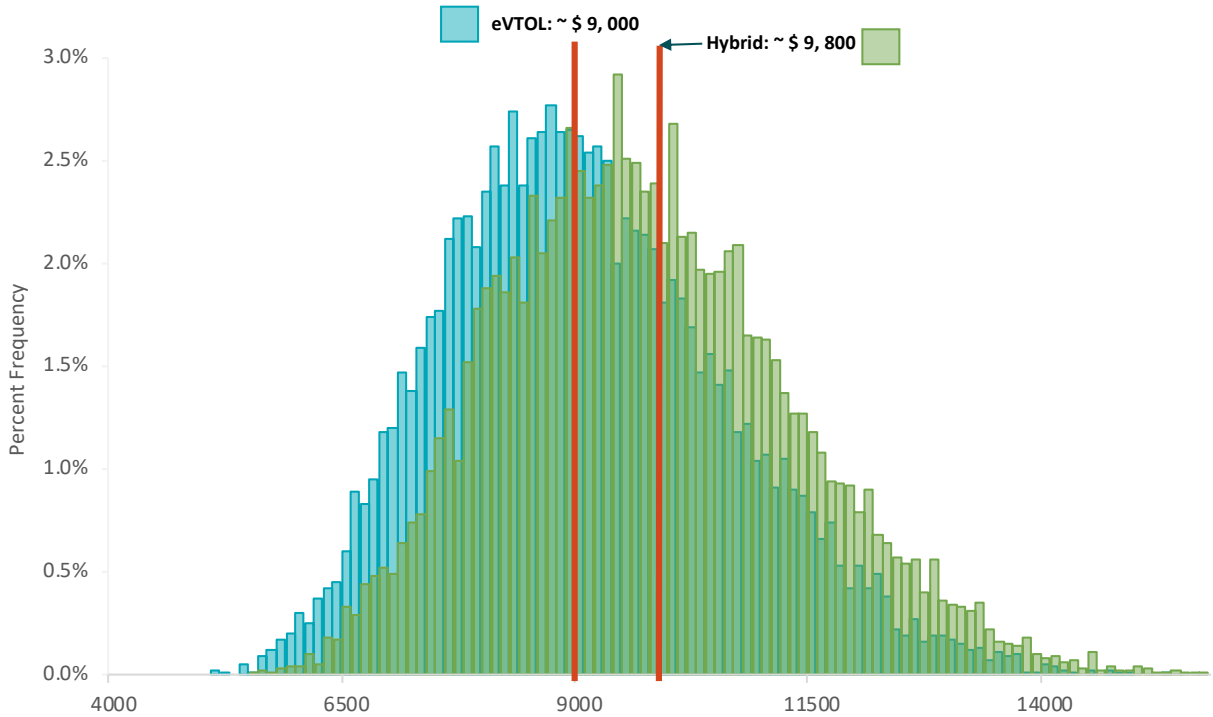


Figure 63: Cost per transport for eVTOLs and Hybrids

Figure 64 shows breakdown of operating costs. We observed that fixed cost for RW, eVTOL, and Hybrid aircraft account for approximately 80% of the overall cost per transport. Therefore, improvements in vehicle efficiency will not affect the cost per transport significantly.

Fixed cost can be reduced if it is spread over a larger number of transports (i.e., increased utilization). However, it must be noted that number of transports for an eVTOL particularly will be affected by high battery recharging time that will increase total call time and reduce availability of eVTOL as compared to Rotary wing. Higher unavailability time was considered as unfavorable to air ambulance as it was found to reduce dispatch reliability explored in greater detail in next sections.

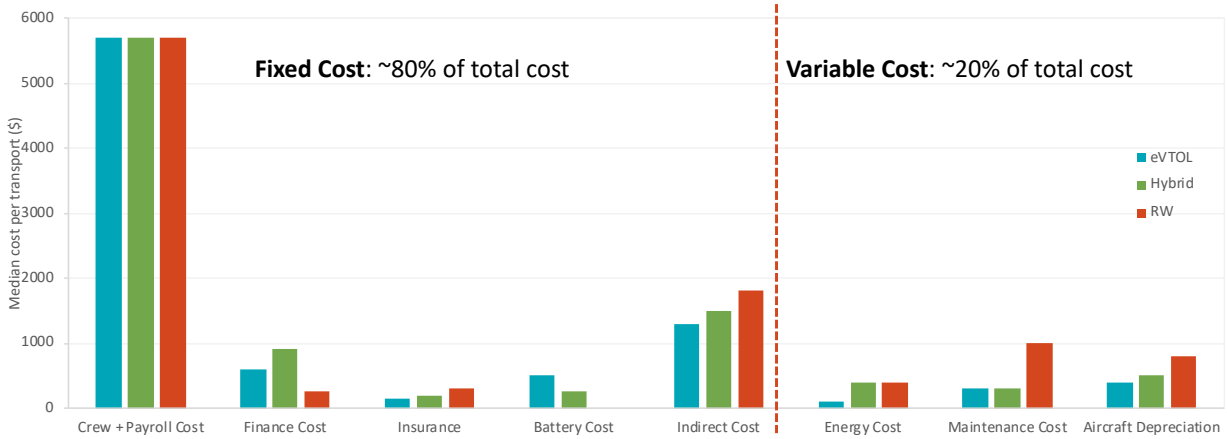


Figure 64: Breakdown of operating cost for different air ambulances

11.5 Scenarios: Revised ConOps and Battery Swapping

Our analysis showed that for an eVTOL air ambulance total battery requirements are significantly high (i.e., approximately 3,500 lbs., which can limit its capability to compete on long air ambulance missions). At an average battery charger maximum power setting of 125 kW, we found that eVTOL's preparation time (i.e., time required to bring the vehicle back in service) was significantly higher due to high battery charging times. Therefore, we consider two scenarios in an effort to reduce total call time:

11.5.1 Scenario 1: Revised ConOps – In the original ConOps, under Transport phase (M), patient was transported from the scene to the medical facilities. For this scenario, we explored battery recharging during patient disembarkation time (~ 5 mins) to reduce overall range requirement, which can reduce battery requirement. We found that this scenario reduced the total range required to 30-180 miles (vs 50-200 miles). Hence, average battery weight in case of eVTOLs was reduced to ~3,200 lbs. (as opposed to ~3,500 lbs.).

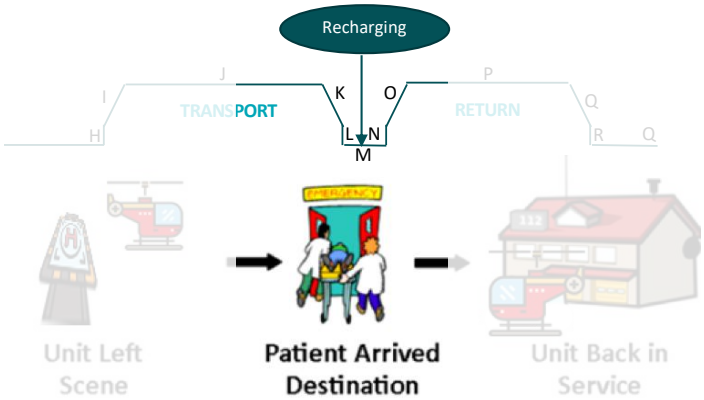


Figure 65: Scenario 1: Revised ConOps

11.5.2 Scenario 2: Battery Swapping – Given high re-charging times, in this scenario, air ambulances relied on swapping batteries when eVTOL returned to the base after each mission to reduce the total call time. Battery swapping was assumed to take around 5 minutes. It is to be noted that in this scenario, cost of an extra battery was added to the cost calculations, while staff and equipment required to swap the batteries were considered as a part of indirect operating costs.

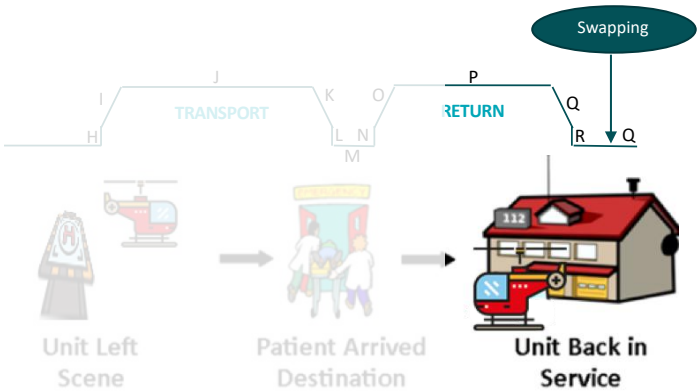


Figure 66: Scenario 2: Battery Swapping

Next, we compared the total call time for eVTOLs and Hybrid with RWs as shown in Figure 67. Dispatch, Chut.Ze, and Scene time were expected to remain same for RW and eVTOL/hybrid. Scene response and transport time reduced for eVTOLs and hybrid due to higher overall speed. However, return time increased significantly for eVTOL (and eVTOL with revised ConOps scenario) due to high battery recharging times, which almost doubled the total call time and approximately halved the availability of the vehicle for next mission when compared to RW. Moreover, reduction in availability of an eVTOL reduced utilization, which

increased the cost per transport making eVTOL an unfavorable option to replace RWs. On the other hand, hybrids and eVTOL with battery swapping capabilities were found to be favorable as they can be utilized ~35% more than current RWs maintaining similar availability standard, potentially reducing cost per transport by ~30%.

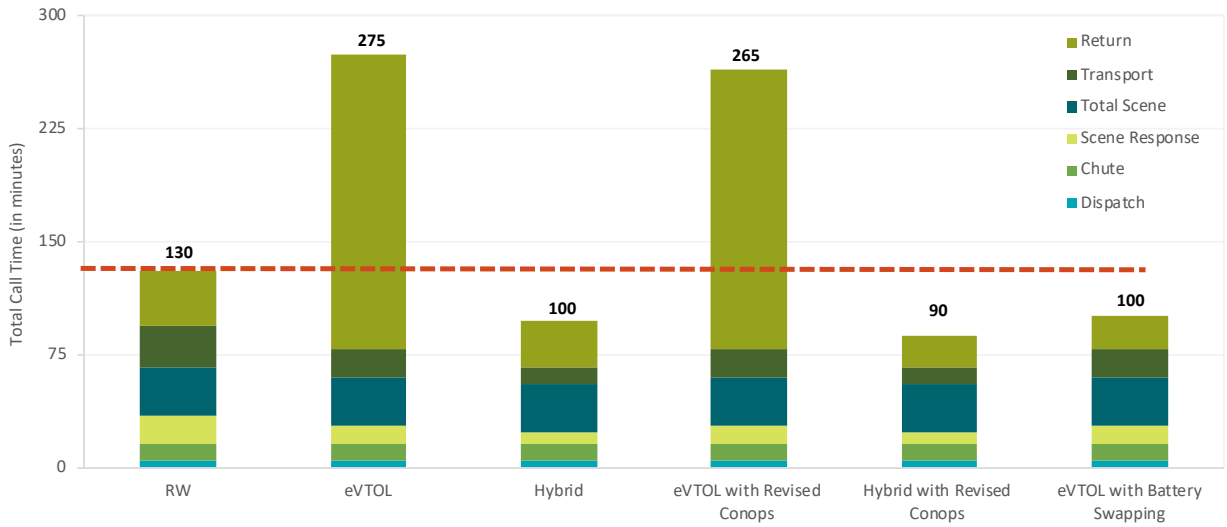


Figure 67: Comparison of total call time

11.6 RW Market Size Capture

The Booz Allen team investigated the suitability of eVTOLs and Hybrid aircraft for the existing RW market. As shown in Figure 68, demand modeling was performed in three main steps: Effective number of transports required/performed, hourly demand distribution and dispatch reliability modeling for different scenarios.

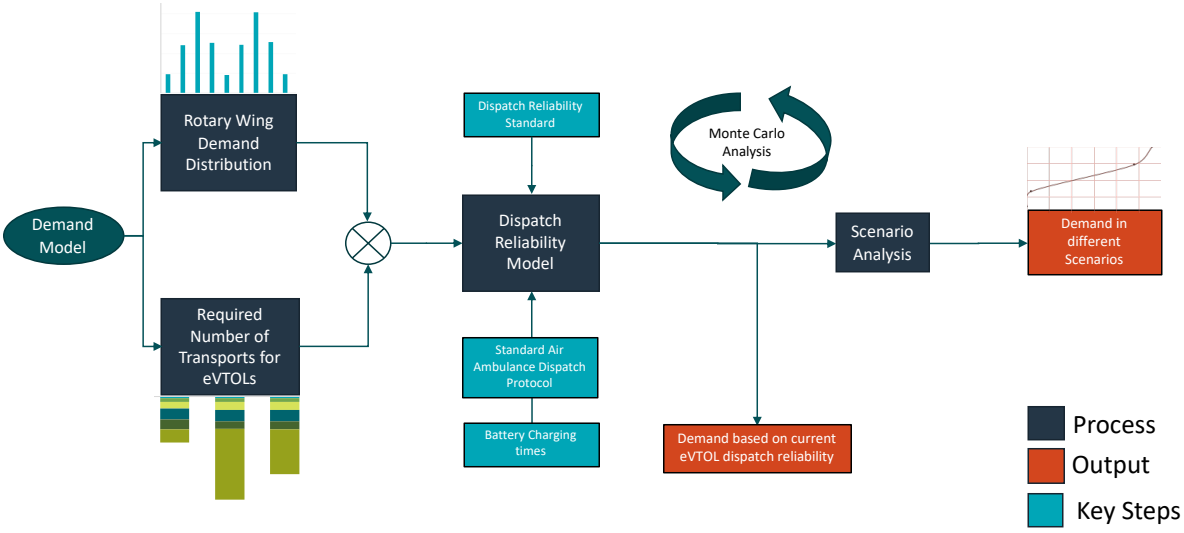


Figure 68: Demand Model for Air Ambulances

Step 1: Effective number of transports – As we noted in the previous section that an increase in total call time for eVTOLs (except battery swapping scenario) decreased the number of transports eVTOLs can complete, thereby increasing cost. To maintain the same cost level as current Rotary Wing market, eVTOLs were required to perform a greater number of transports (i.e., 2.15x for eVTOL and 2.1x for eVTOL with revised ConOps in comparison to RWs (each RW on average completes 350 transports annually)). On the

other hand, hybrids and eVTOLs with battery swapping capabilities were found to reduce the total call time, which made them an attractive option to replace current RWs.

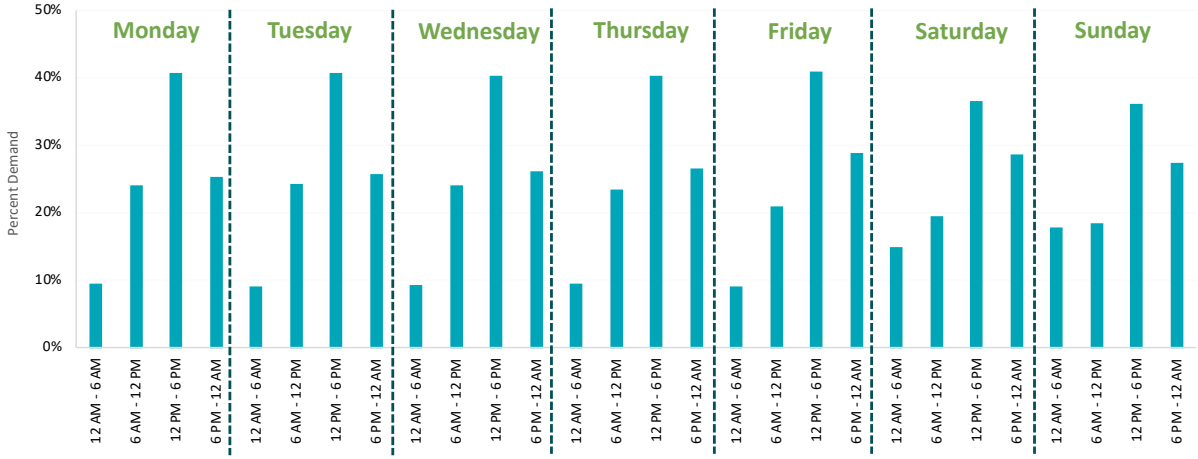


Figure 69: Demand Distribution of RW Market by Hour and Day of Week Averaged over 2014-2016

Step 2: Hourly Demand Distribution – We assumed an average week across all the bases in the U.S. and found that each day of the week followed a similar trend where demand peaked between 12 pm – 6 pm while the demand was found to be lowest between 12 am – 6 am as shown in Figure 69. On average, over 40% of the air ambulance events were completed between 12 pm – 6 pm while only 10% were performed between 12 am – 6 am.

Step 3: Dispatch Reliability – Air Medical Transport follows certain dispatch protocols that consider the need of minimization of time, weather considerations, availability, safety etc., before deploying a RW aircraft as shown in Figure 70.

FACTORS INFLUENCING AIR AMBULANCE DISPATCH DECISION

Patient Requirements:

- **Minimized time outside hospital:** Patient must minimize time spent outside a hospital environment
- **Current facility unable to provide services:** Needs time-sensitive evaluation or procedure outside the capacity of the current facility
- **Critical care life support necessary:** Requires critical care support not available in ground transportation

Variables:

- **Passenger Weight:** Must be within allowable range for air transport
- **Helipad Accessibility:** Destination facility must have helipad or close geographic access to one
- **Weather Conditions:** Current and predicted weather conditions must be favorable for air transport

Local Constraints:

- **Area unsuitable for ground transport:** Ground transportation unavailable or unsuitable for transport
- **Lack of EMS coverage:** Deploying ground transportation leaves local area without adequate EMS coverage

Figure 70: Dispatch protocol as per Emergency Medical Services 2015

Next, we set up a dispatch reliability model that calculated the probability of events for which an eVTOL or Hybrid ambulance was unavailable. In the previous sections, we established that eVTOLs (without battery swapping capabilities) will be required to perform a greater number of transports to maintain the same cost level as RW. Therefore, an increased number of required transports will increase the probability of vehicle being unavailable to serve an emergency event, thereby reducing dispatch reliability. We found eVTOLs dispatch reliability to be around 90%, which is well below the industry standard of 99% as shown in Figure 71.

However, on distributing the demand on an hourly basis (step 2), we found that eVTOLs can serve the 10% of the total demand between 12 am – 6 am maintaining the same dispatch reliability as RW. On the other hand, hybrids were found to serve 100% of the available demand.

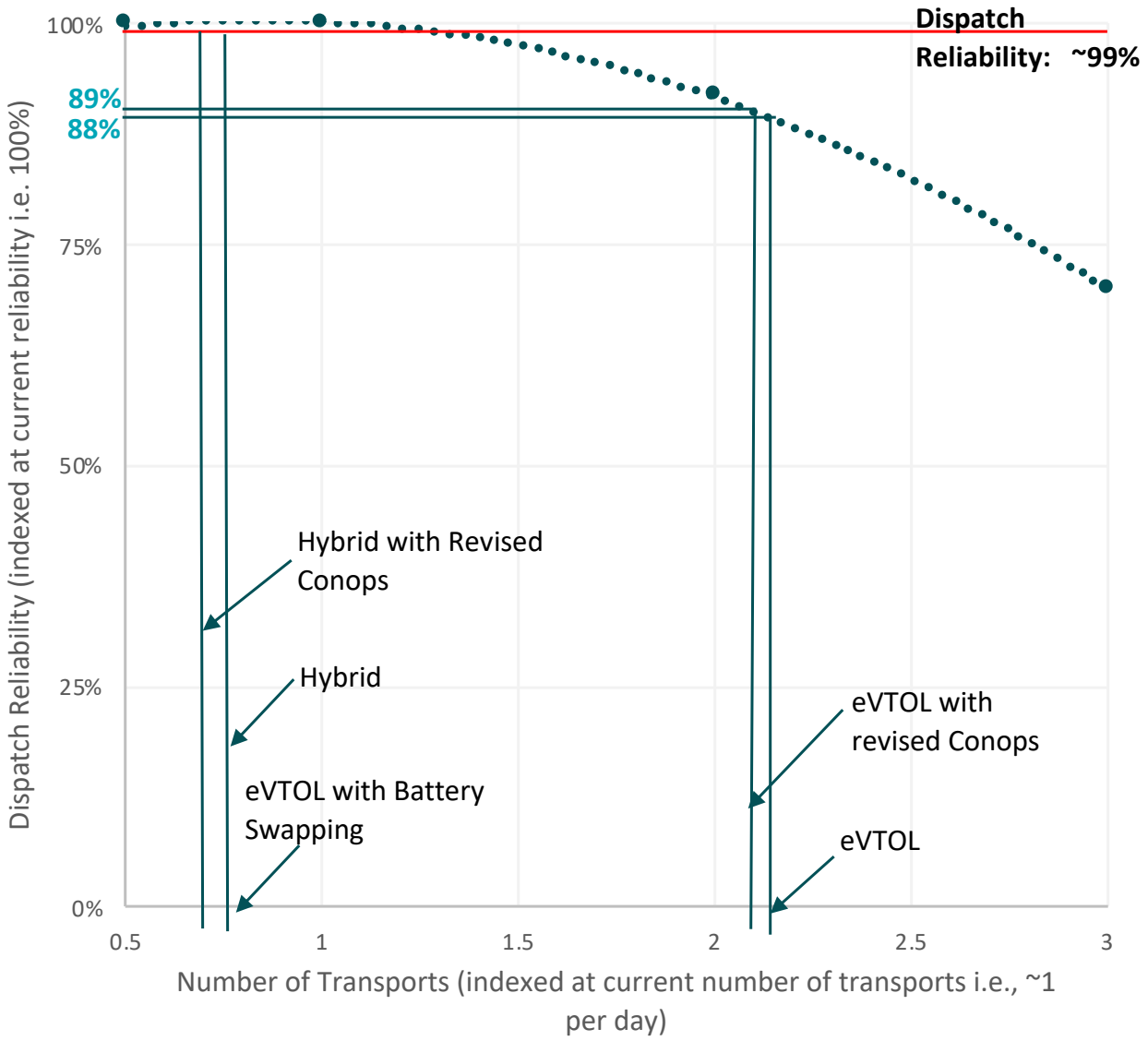


Figure 71: Dispatch Reliability of air ambulances

Finally, we observed that the battery recharge rates need to be increased by a factor of 4 for eVTOLs to compete with the RW and address total available RW market at similar dispatch reliability levels and cost per transport. eVTOLs with battery swapping capabilities and hybrid aircraft could potentially address the 100% of this market. Technology innovation (i.e., increase in recharge rate and battery swapping capabilities) is required for eVTOLs to serve the air ambulance market in the long term.

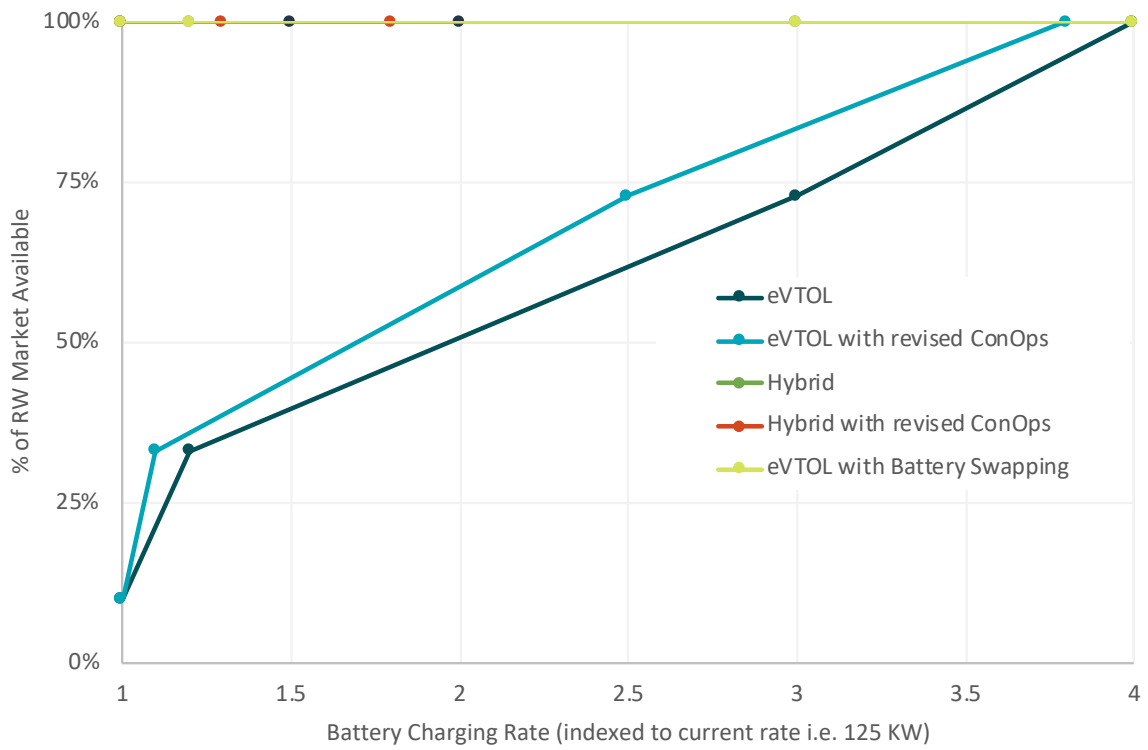


Figure 72: RW Market Capture Probabilities

11.7 Air Ambulance Market Summary

Key Findings	Key findings uncovered during the Air Ambulance market survey include: • eVTOLs and hybrid aircraft are expected to compete with existing Rotary Wing market for the near term due to competition from ground ambulances and high range requirements for fixed wing market • Median cost of operating an eVTOL and hybrid air ambulance, at RW utilization rates, is ~ $9, 000 and ~9, 800 per transport respectively of which ~80% is fixed costs and ~20% variable costs • Battery recharging time is high, thus making the vehicle unavailable for longer times (reducing reliability). • Battery recharge rate will need to be increased approximately 4 times to current rate for eVTOLs to address the total available RW market • Hybrid vehicles have faster return time than eVTOLs and conventional helicopters. Therefore, Hybrids can be utilized ~35% more than current RW maintaining the desired reliability levels. This could potentially reduce cost per transport by ~30%. Therefore, tilt rotor hybrids are an attractive option to replace traditional RWs • Battery swapping capability is more preferred eVTOLs due to similar level of dispatch reliability as current RW market

12.0 LESSONS LEARNED AND RECOMMENDATIONS

The legal and regulatory analysis demonstrated that though lawmaking is usually slow and tedious, legislation is moving quickly to keep pace with the advancements in UAS technology, which helps reduce the gap towards enabling UAM. During the course of this study, we saw the introduction of the UAS IPP which is helping drive enabling rules that would allow more complex operations, the passing of the FAA Reauthorization Act of 2018 which mandates FAA to make regulations within the year for the UAS carriage of property for compensation or hire, among other items, and movements within EASA to regulate VTOL aircraft with a passenger seating configuration of 5 or less and a maximum certified take-off mass of 2,000kg or less. What stood out as barriers at the beginning of the study have eased into opportunities as many of these developments unfolded near the end of this project. With that in mind, we recommend that any future studies emphasize the need to be agile in a quickly changing legal environment, and that the focus on "barriers" be shifted to "opportunities" so that NASA can find ways to design, develop, and test advanced UAM technologies that will translate into enabling legislation.

The societal barrier analysis demonstrated the need to conduct further research by employing a flight simulator and/or an actual certified aircraft as part of a pilot program or test clinic. Simulations or flight experience in a UAM aircraft might give respondents a more realistic understanding of UAM travel. Another option would be to further study the influence of congestion on UAM perceptions. In our survey, we did not collect data on a respondent's commute time or attitude toward congestion. Interestingly, commute distance was slightly significant in regression model. To better understand this, we examined the city of residence as a possible predictor related to commute time, as each of the cities has a different mean commute time. According to the 2016 ACS, mean travel time to work is 29.5 minutes in Houston, 29.6 minutes in Los Angeles, 35.9 in New York City, 32.1 minutes in the San Francisco Bay Area, and 34.4 minutes in Washington, D.C. The binomial logistic regression model had statistically significant coefficients for Los Angeles and the San Francisco Bay Area in contrast to Houston. However, respondents from Houston and Los Angeles have shorter mean commute times and yet are more willing to use UAM. This indicates the mean commute time for the city is not a good stand-in for a respondent's willingness to use UAM or perhaps our respondent population was not representative of each of the cities with respect to commute time. Further study of the role of congestion as a predictor of UAM interest may be fruitful to explore in a future project.

From the weather analysis, we found that synthesis of potential weather impacts across a broad range of operations and vehicles is a challenge. For example, IFR conditions could be highly impactful if assuming piloted VFR-only operations, but minimal for fully-automated vehicles equipped with sensors to enable IFR flight. The impact scores would likely vary depending on operation specifics. For a future study, we recommend exploring some specific case examples to apply detailed assumptions on vehicle and operations to more fully explore the range in weather impacts. This would also enable weather barriers to be more fully captured into the market analysis supply and demand models.

Finally, market analysis demonstrated the uncertainties that exist in the various assumptions made throughout the analysis in relation to availability and specifications of technology, Air Traffic Control capabilities, ground infrastructure development, public acceptance, laws and regulations. For example, assumptions related to technology and operations were made through literature review and interviews with SAG members. As such, the assumptions seemed realistic, a high priority area of future work should be to update them with the development of technology and as operations are planned. Our analysis also demonstrated the implications of different technology, operations and market related scenarios. For example, Autonomous cars and reduced importance of travel time were found to severely constrain the demand for Air Taxis, while autonomy, high network efficiency and increased congestion were found to increase demand. For a future study, we recommend detail exploration of technology infusion trends (both spatial and temporal) in the entire transportation sector that could affect UAM markets. We also recommend to study environment sustainability (noise, emissions, ecological and visual pollution) of UAM at a system level. In our study, we identified 36 potential UAM markets and focused our analysis on ten urban areas. Our extrapolation of results to all of U.S. may not have captured the nuances of other urban areas. Therefore, we recommend including more urban areas for detailed analysis, and also study market feasibility of the remaining markets to understand the true scale of operations. Supply chain of manufacturers should be analyzed taking into account global demand, and aircraft price (based on economies of scale), fleet mix and evolution should also be studied.

Appendix

Appendix 1: Societal Barriers
Appendix 2: Weather Analysis
Appendix 3: Market Analysis

13.0 APPENDIX

The appendix provides more details to following sections of the analysis: Societal Barriers, Weather Analysis, and Market Analysis

Appendix 1 – Societal Barriers (General Population Survey)

13.1.1 Travel Behavior

Many of the trips were recreational, with 39% urban recreational trips (i.e., a trip within the city) and 29% long distance recreational trips (i.e., a trip between cities). Respondents living in the New York Metropolitan area were more likely to travel within the city (45%), while respondents living in Houston had slightly higher than average trips to healthcare services and long-distance recreational trips, compared to the other cities. The trip purpose by city is displayed in Figure 73 below.

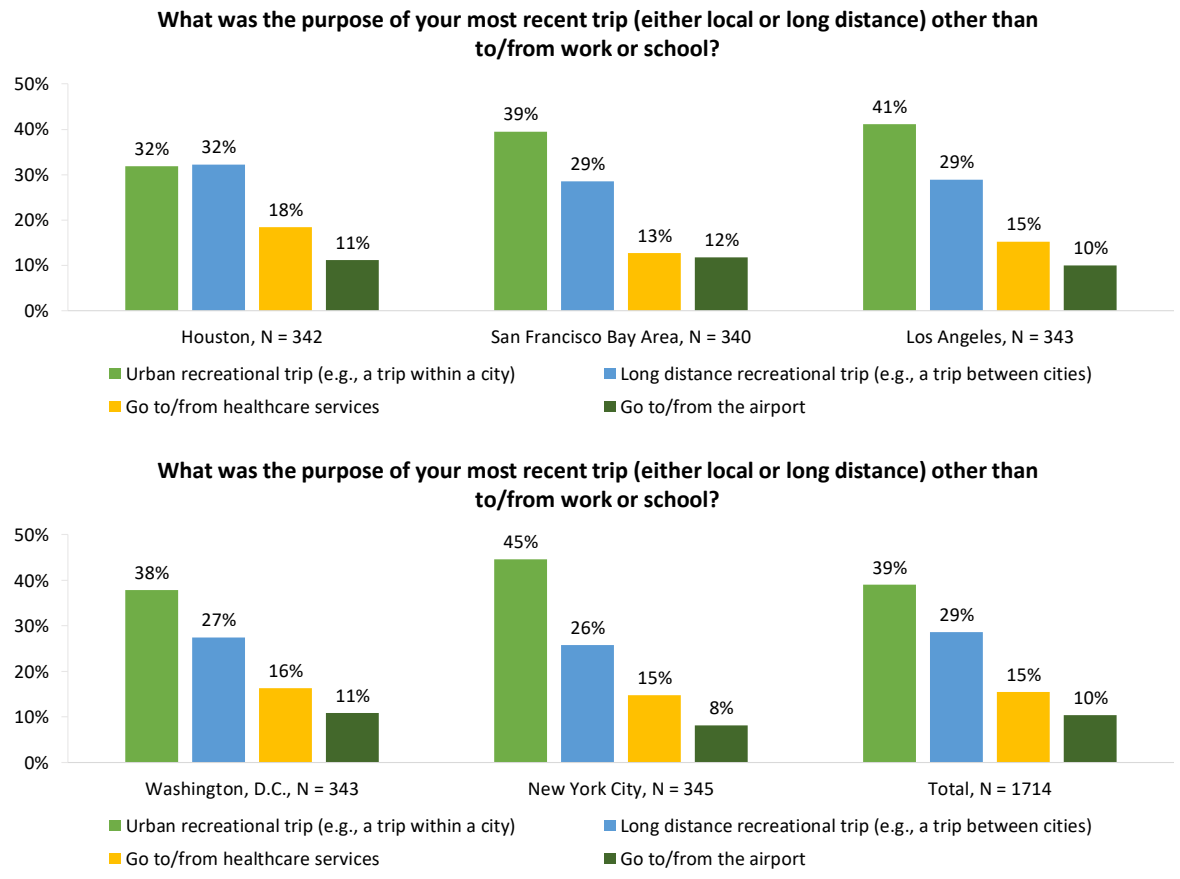


Figure 73: Recent Trip Purpose

Next, we linked the trip purpose with the distance traveled to produce the distributions in Figure 74 below. Urban recreational trips and healthcare-related trips were generally skewed toward distances less than 10 miles, while the majority of long-distance recreational trips (54% of 489 trips) were over 100 miles. One potential limitation of the trip distance findings for healthcare services was the variance in trip type; UAM may not be suitable for all trip types. Routine medical appointments, urgent care, or emergency trips in air ambulances were captured as healthcare-related trips. Finally, of the 176 respondents who traveled to the airport for their most recent trip, 30% were over 100 miles away, indicating that a significant portion of the respondent population traveled quite far for air travel. There could be a number of reasons for this behavior, particularly in markets where there are multiple large domestic and international airports. For example,

someone living in Northern Virginia may travel to Baltimore's BWI for a cheaper fare or use a particular carrier rather than using their closest airport (i.e., Dulles or Regan National).

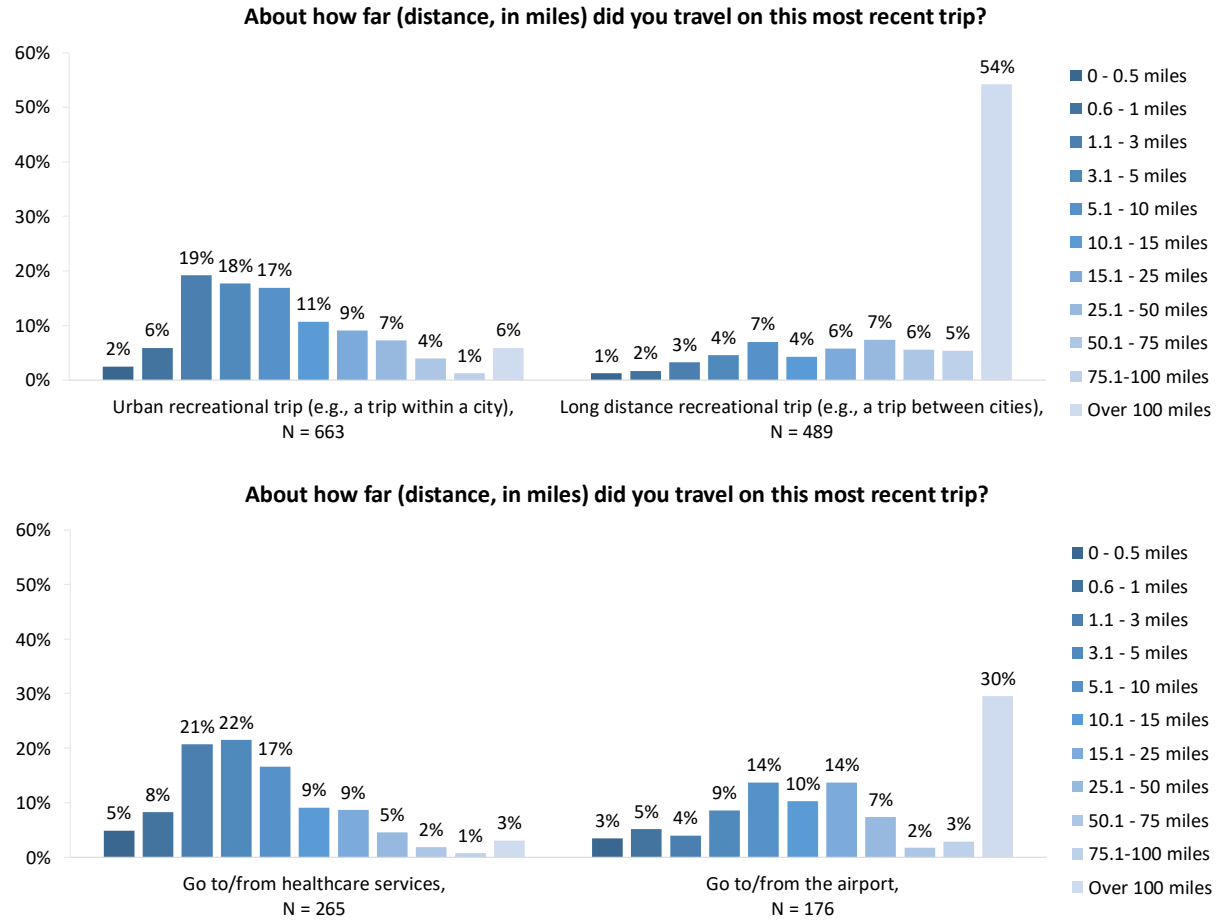
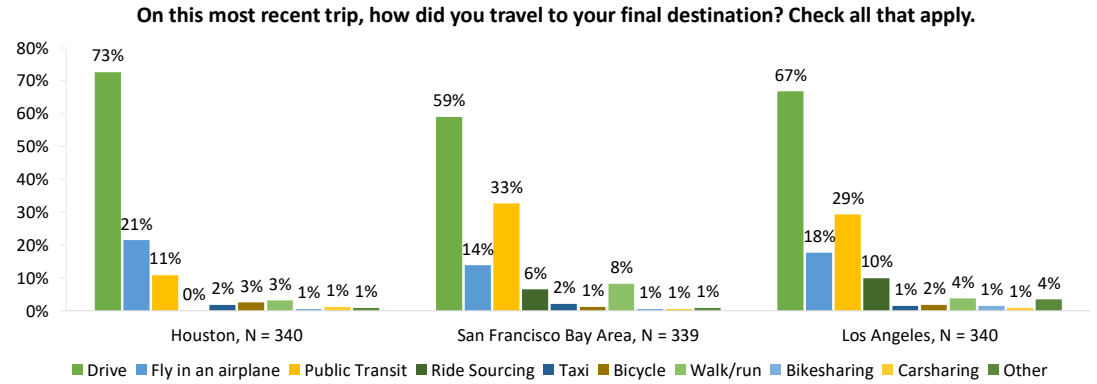


Figure 74: Most Recent Trip Distance

Figure 75 below displays the travel modes used to the most recent trip destination. The highest modal share for the most recent trip was driving, with approximately 60% of respondents using a car for the trip, followed by public transit at 31%. Sixteen percent of the trips were traveled by airplane. Houston was heavily skewed toward drivers (73%) with low public transit use (11%). Not surprisingly, New York City respondents were much less likely to drive (33%) and were skewed toward using public transit (54%).

Respondents were presented a series of questions that we designed to capture their typical commute behavior; these questions were based on the questions asked regarding the most recent non-commute trip. Respondents were asked to select the transportation modes they use to commute to work or school, how many days per week they commute, and the distance (one-way) of their commute. The typical commute distance was generally between 1 and 10 miles in all five cities. Driving (62%), public transit (56%), telecommuting (54%), and walking (26%) were all popular modes for commuting. The percentages add up to more than 100%, as respondents could use more than one mode during their commute. For example, a respondent could have a multi-modal commute where they rode their bicycle to a light rail station and then took light rail to work. This would result in the selection of two modes. Respondents were also given the ability to select: "telecommute." Some of the respondents telecommute several days a week and then travel to a workplace for other days throughout the week, leading to overlap between physical modes and telecommuting in Figure 76. We also asked respondents to identify the factors that impact how they choose to travel to a destination. Cost and convenience were the most important motivators impacting modal choice.



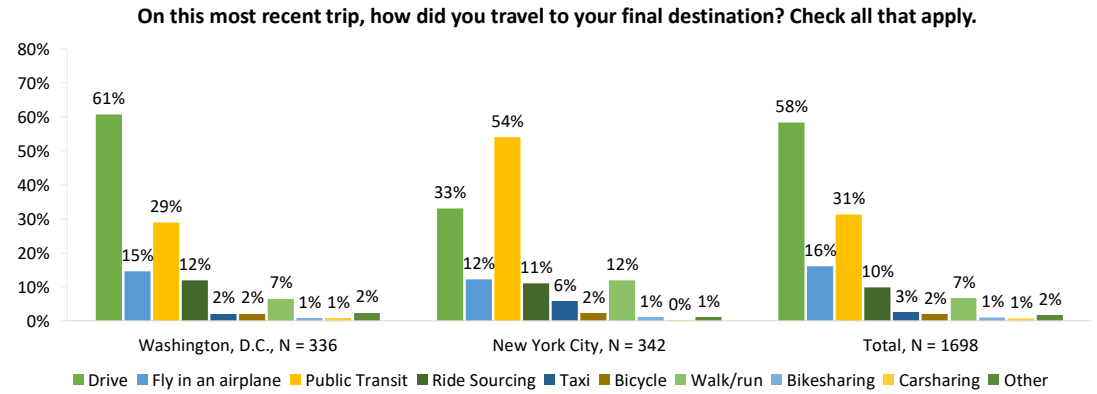
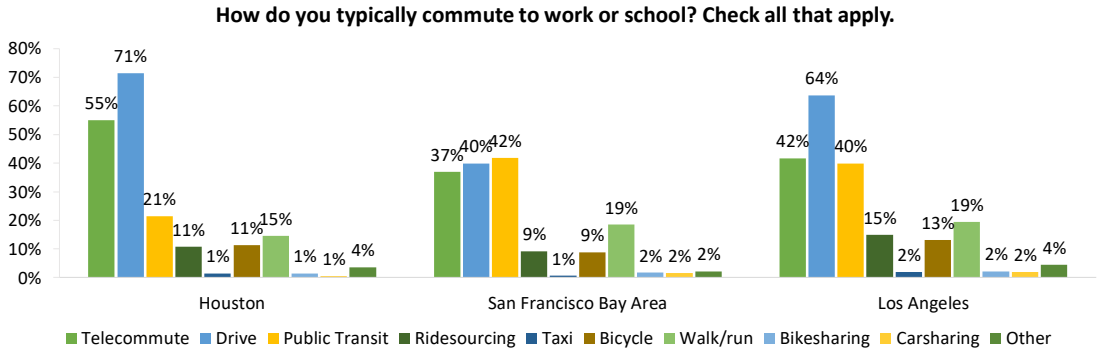


Figure 75: Most Recent Trip Mode



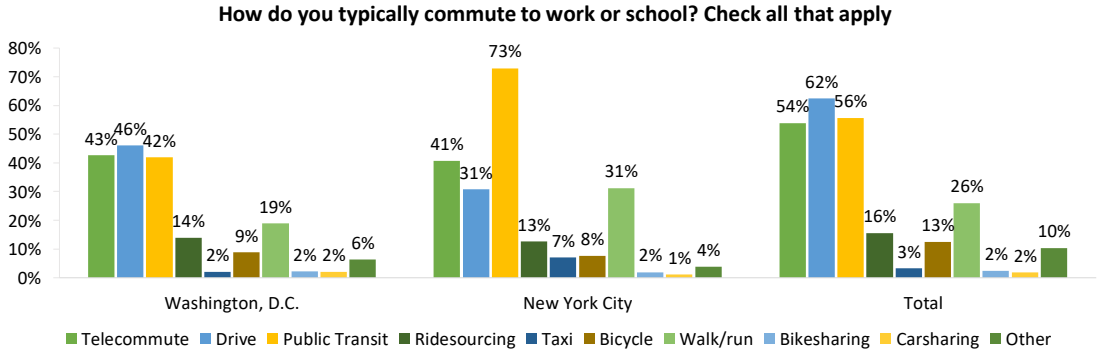
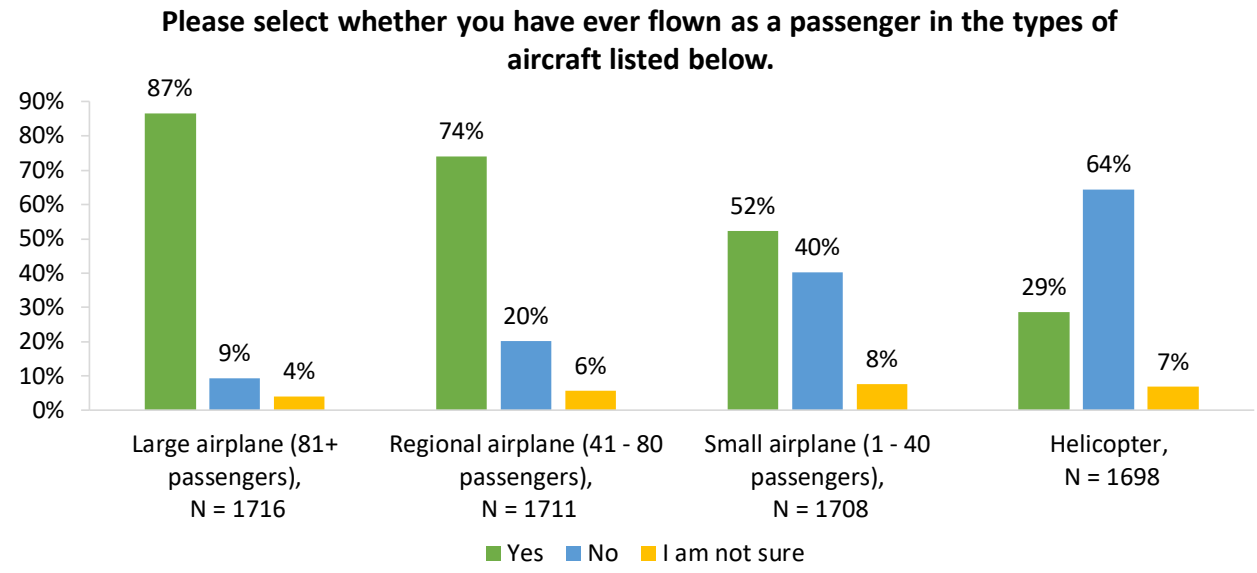


Figure 76: Commute Mode

13.1.2 Familiarity with Aviation and Existing Preferences

Most respondents indicated that the purpose of their flights is usually leisure and recreation, as indicated in Figure 77.



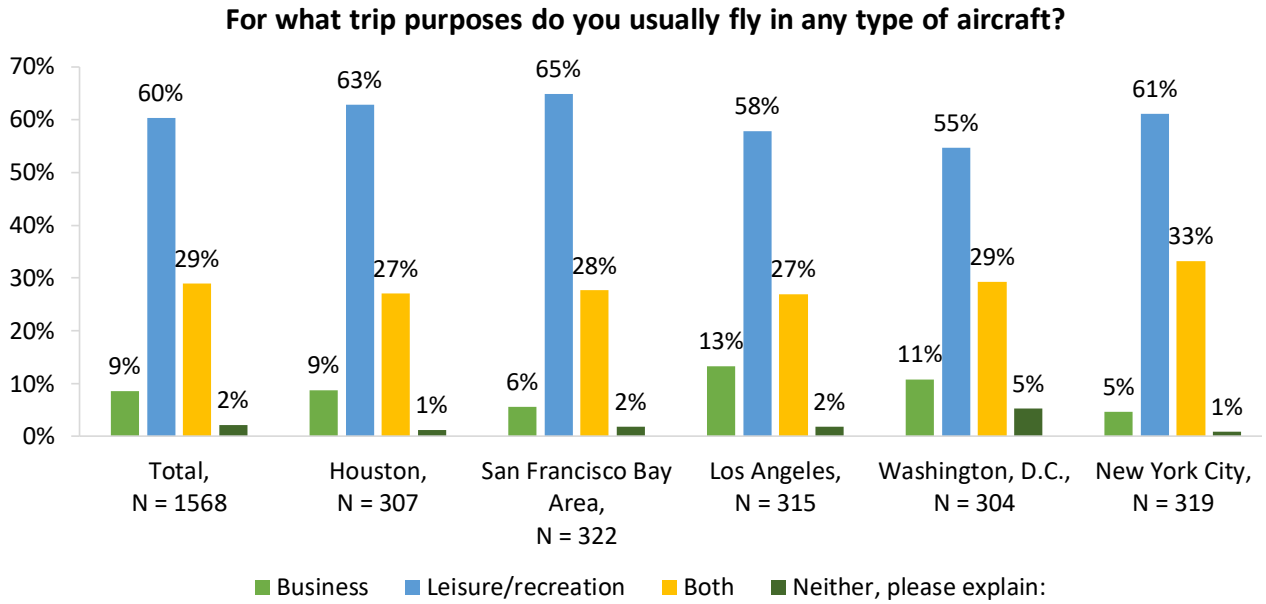


Figure 77: Aircraft Exposure

Figure 78 indicates that across all cities, 47% of respondents fly 1 to 6 times per year, followed by 26% of respondents who fly less than 1 time per year.

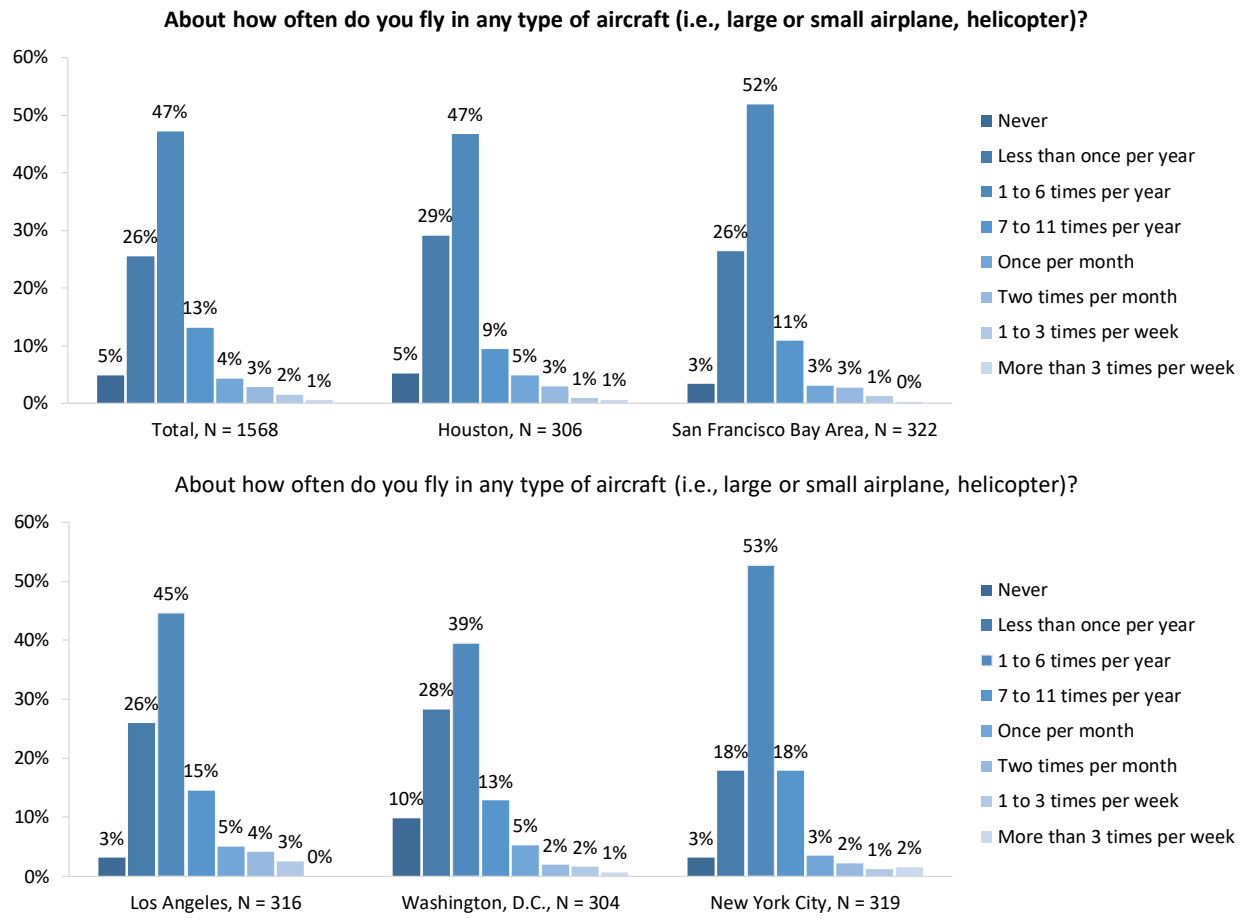


Figure 78: Flight Frequency

We designed several questions to explore the factors that influence a respondent's decision to travel by air and existing preferences from their flight experience. Regarding factors that encourage or discourage respondents from flying more frequently, the respondent was presented a list of factors related to the decision to fly, such as: flexibility, total flight time, cost, and the ability to visit places out of town. The respondent was presented a 5-point Likert scale ranging from "very much encourage" to "very much discourage" and was asked to rate each of the factors. Of the factors related to the decision to book a flight, cost was identified as the most important factor, as it had the highest percentage of respondents who found it "very much encouraging," as well as the highest percentage of respondents who found it discouraging. The results of this question are enumerated in Figure 79 below.

Next, the respondent was asked to similarly rate factors related to their flying experience, such as the check-in experience, security process, and on-board experience. The results of this second question can be viewed in Figure 80 below. Many of the factors related to the flying experience encouraged passengers to fly more frequently, except for "anxiety around flying" and "impact on carbon footprint." Respondents were relatively ambivalent toward these two factors. It is possible that people do not have anxiety about flying, or if they do, perhaps it does not impact their decision to fly.

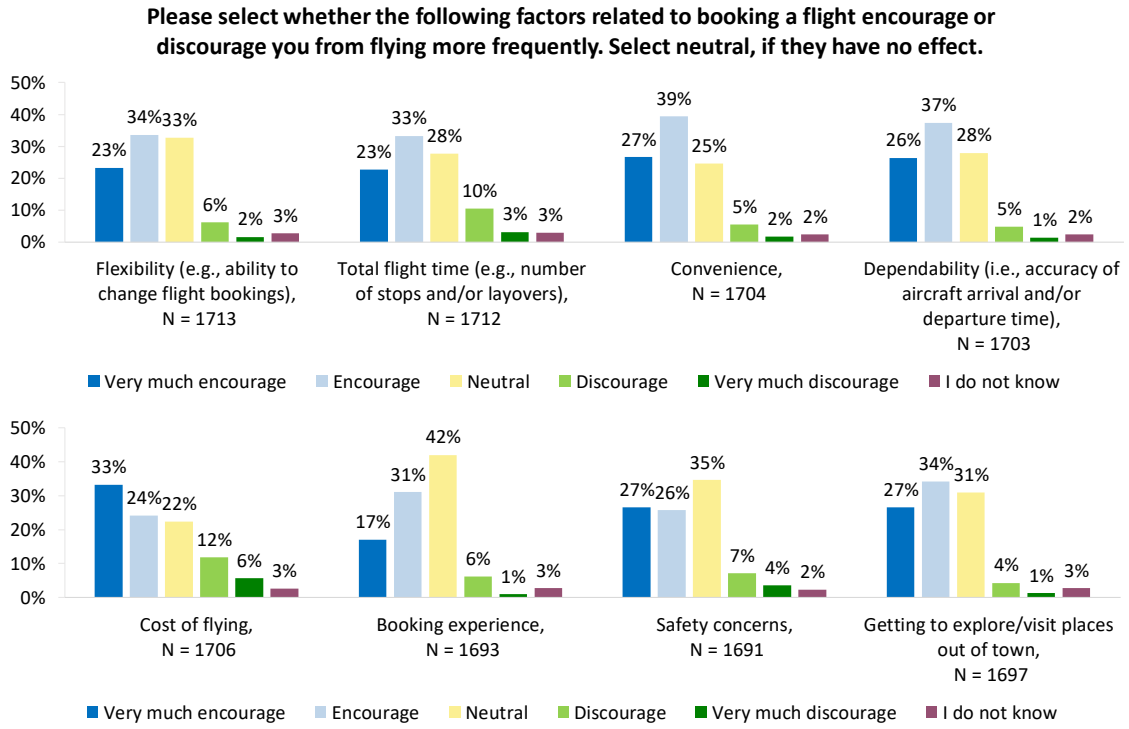


Figure 79: Factors affecting Decision to Fly

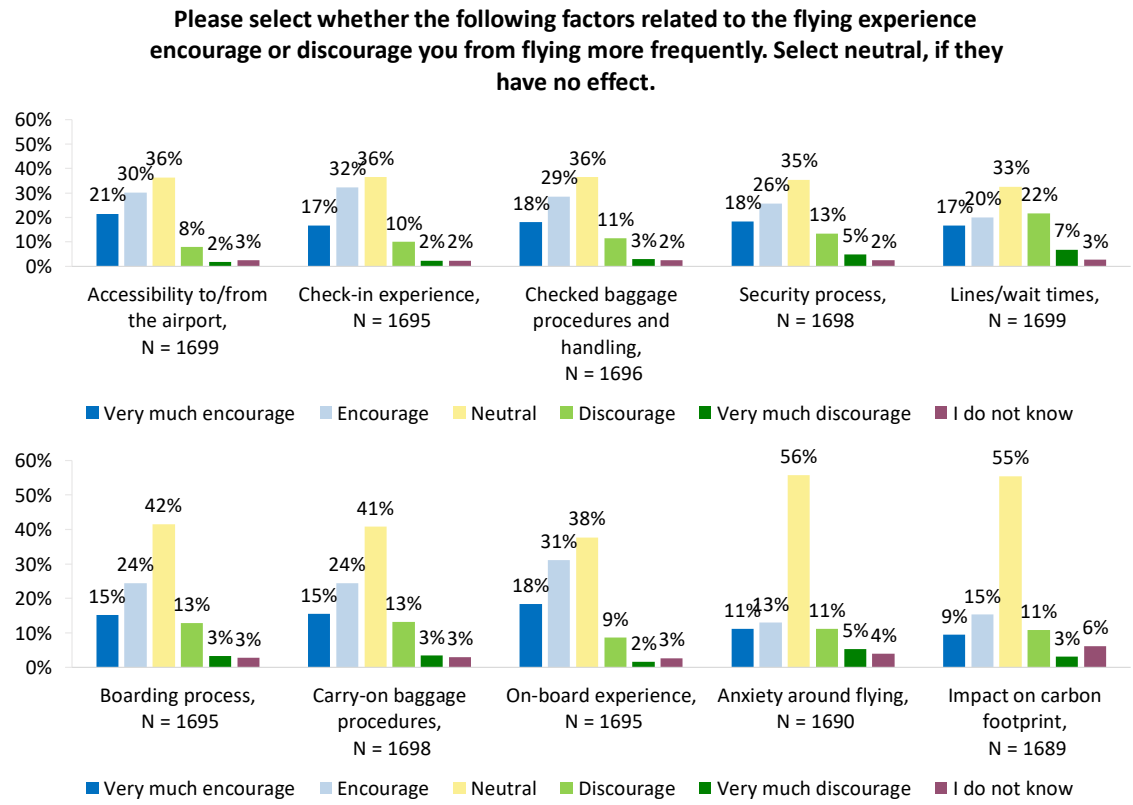


Figure 80: Factors Affecting Flight Experience

Regarding the onboard flying experience, respondents considered physical comfort as the most important factor toward a satisfactory flying experience. 41% of the respondents viewed “a comfortable seat” as very important, followed closely by minimal turbulence and a pleasant ambient temperature. On-board amenities and in-flight entertainment received positive responses, but were not viewed as essential to the on-board experience in comparison to the other features. The full results are presented in Figure 81.

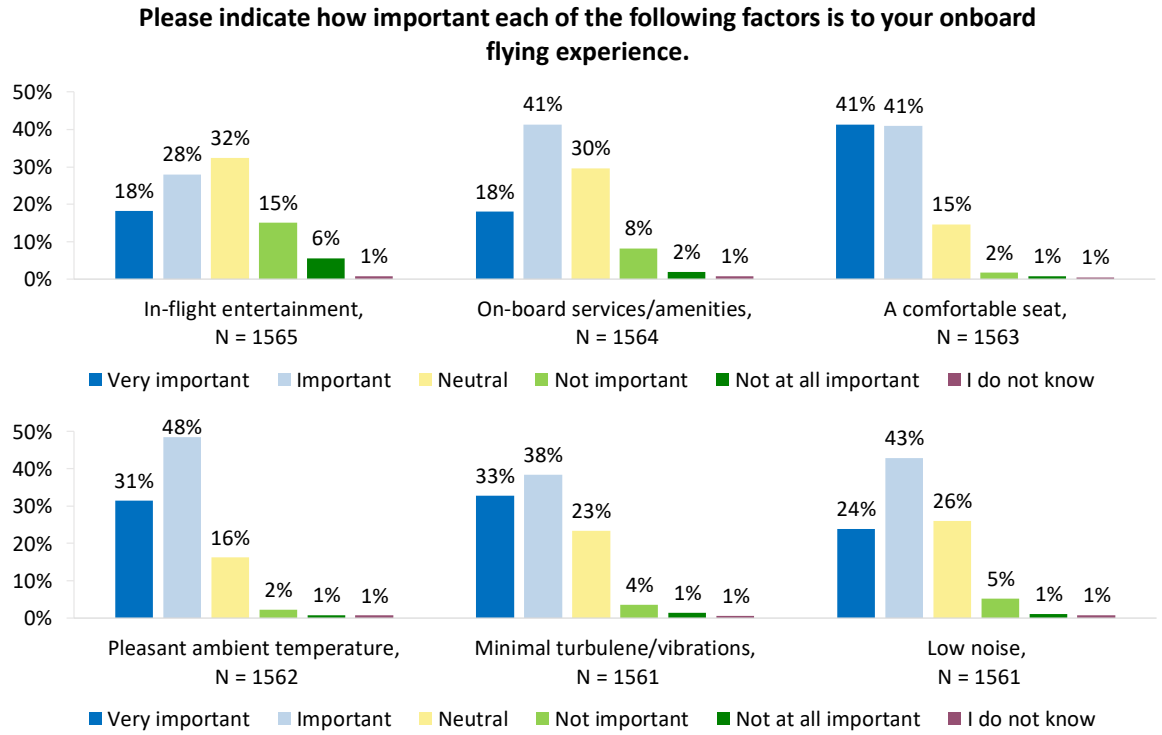


Figure 81: On-Board Experience

13.1.3 UAM Perceptions

Table 19: Initial Reactions

	Excited	Happy	Neutral	Confused	Concerned	Surprised	Skeptical	Amused
GEOGRAPHIC LOCATION				**Survey Results**				
Houston, N = 344	32%	24%	27%	8%	9%	11%	19%	3%
San Francisco Bay Area, N = 337	33%	25%	27%	8%	9%	11%	20%	3%
Los Angeles, N = 345	32%	24%	27%	8%	9%	11%	19%	3%
Washington, D.C., N = 341	32%	24%	27%	8%	9%	11%	20%	3%
New York City, N = 344	32%	24%	27%	8%	9%	11%	19%	3%
GENDER				**Survey Results**				
Female, N = 976	26%	22%	26%	10%	11%	11%	20%	4%
Male, N = 734	37%	23%	23%	6%	10%	8%	18%	4%
RACE/ETHNICITY				**Survey Results**				
African American, N = 291	22%	17%	26%	4%	2%	3%	7%	2%
American Indian or Alaskan	12%	19%	42%	8%	8%	0%	0%	0%
Asian, N = 206	25%	13%	23%	5%	4%	3%	8%	1%
Caucasian/White, N = 982	20%	14%	17%	6%	5%	2%	10%	1%
Hispanic or Latino, N = 166	26%	19%	19%	2%	2%	5%	2%	2%
Middle-Eastern, N = 15	33%	13%	13%	0%	7%	7%	7%	0%
Native Hawaiian or Pacific	0%	13%	19%	6%	0%	13%	0%	0%
Pakistani, etc.), N = 5	0%	20%	20%	20%	0%	0%	0%	0%
Southeast Asian, N = 9	33%	11%	22%	11%	0%	0%	0%	0%
Other, N = 25	32%	4%	16%	16%	0%	0%	4%	0%
INCOME				**Survey Results**				
Less than $10,000, N = 78	14%	17%	40%	8%	3%	4%	10%	3%
$10,000 - $14,999, N = 53	19%	23%	30%	6%	6%	6%	6%	6%
$15,000 - $24,999, N = 101	25%	12%	36%	7%	3%	6%	7%	3%
$25,000 - $49,999, N = 212	28%	15%	27%	8%	5%	3%	11%	2%
$50,000 - $74,999, N = 210	28%	22%	25%	7%	4%	5%	8%	0%
$75,000 - $99,999, N = 192	30%	30%	14%	7%	5%	2%	9%	1%
$100,000 - $149,999, N = 182	36%	14%	25%	4%	6%	1%	12%	2%
$150,000 - $199,999, N = 101	27%	21%	20%	8%	6%	6%	9%	2%
$200,000 or more, N = 112	35%	12%	21%	7%	11%	4%	11%	0%
AGE				**Survey Results**				
18 - 24 years, N = 110	22%	25%	34%	5%	2%	4%	5%	2%
25 - 34 years, N = 271	32%	28%	19%	4%	4%	3%	8%	1%
35 - 44 years, N = 191	43%	16%	17%	6%	5%	2%	8%	3%
45 - 54 years, N = 132	30%	16%	21%	8%	9%	3%	9%	2%
55 - 64 years, N = 178	26%	15%	29%	9%	7%	4%	8%	1%
65 - 74 years, N = 169	14%	12%	33%	9%	6%	4%	18%	1%
75+ years, N = 42	10%	14%	31%	10%	7%	2%	24%	0%
EDUCATION				**Survey Results**				
Less than high school, N = 15	27%	20%	33%	7%	7%	7%	0%	0%
Currently in high school, N = 11	18%	0%	64%	0%	0%	0%	0%	9%
High school GED, N = 196	23%	17%	34%	7%	3%	2%	10%	3%
Currently in 2-year college, N = 45	20%	31%	29%	4%	0%	4%	4%	4%
2-year college degree, N = 128	27%	20%	26%	5%	6%	5%	10%	1%
Currently in 4-year college, N = 72	22%	31%	25%	3%	1%	4%	13%	0%
4-year college degree, N = 445	30%	18%	24%	7%	6%	4%	9%	1%
Currently in post-graduate degree, N = 30	23%	23%	20%	17%	3%	0%	7%	3%
Post-graduate degree (MA, MS, PhD, MD, JD, etc.), N = 363	29%	15%	22%	7%	7%	4%	13%	1%

Ordinal Logistic Regression

Table 20: Crosstabs on Socio-Demographic Variables

	Willing				
EDUCATION	**Strongly agree**	**Agree**	**Neutral**	**Disagree**	**Strongly disagree**
Less than high school, N = 19	37%	21%	37%	0%	5%
Currently in high school, N = 15	20%	40%	40%	0%	0%
High school GED, N = 242	20%	30%	36%	9%	6%
Currently in 2-year college, N = 51	29%	24%	37%	8%	2%
2-year college degree, N = 163	18%	35%	32%	10%	6%
Currently in 4-year college, N = 82	17%	41%	29%	10%	2%
4-year college degree, N = 568	25%	33%	29%	8%	5%
Currently in post-graduate degree, N = 37	27%	27%	35%	8%	3%
Post-graduate degree (MA, MS, PhD, MD, JD, etc.), N = 468	24%	32%	28%	13%	3%
INCOME	**Strongly agree**	**Agree**	**Neutral**	**Disagree**	**Strongly disagree**
Less than $10,000, N = 94	23%	23%	34%	14%	5%
$10,000 - $14,999, N = 64	13%	42%	36%	6%	3%
$15,000 - $24,999, N = 128	21%	30%	40%	6%	3%
$25,000 - $49,999, N = 269	21%	30%	32%	9%	7%
$50,000 - $74,999, N = 267	22%	37%	28%	11%	2%
$75,000 - $99,999, N = 241	32%	30%	27%	7%	4%
$100,000 - $149,999, N = 229	24%	38%	27%	7%	4%
$150,000 - $199,999, N = 119	28%	27%	31%	13%	2%
$200,000 or more, N = 146	25%	36%	21%	15%	3%
AGE	**Strongly agree**	**Agree**	**Neutral**	**Disagree**	**Strongly disagree**
18 - 24 years, N = 131	28%	35%	32%	2%	3%
25 - 34 years, N = 348	32%	32%	28%	5%	3%
35 - 44 years, N = 234	29%	31%	21%	15%	5%
45 - 54 years, N = 168	22%	30%	30%	13%	4%
55 - 64 years, N = 215	18%	32%	35%	12%	4%
65 - 74 years, N = 219	11%	38%	32%	12%	7%
75+ years, N = 59	14%	24%	37%	20%	5%

Table 21: Ordinal Regression Model

	Estimate	Std. Error	Z Value	Pr(>|z|)	
Dependent variable threshold coefficients					
Strongly disagree | Disagree	-3.32E+00	0.23830	-13.953		
Disagree | Neutral	-2.00E+00	0.21600	-9.280		
Neutral | Agree	-2.82E-01	0.20840	-1.353		
Agree | Strongly agree	1.35E+00	0.21240	6.352		
Covariate variables					
Age	-1.08E-02	0.00278	-3.871	0.000108	***
Income	1.28E-06	0.00000	1.451	0.333130	
Commute Distance	7.35E-03	0.00374	1.965	0.049428	*
Factor variables					
Gender (Male)	3.42E-01	0.09117	3.754	0.000174	***
Familiarity					
No	-3.00E-01	0.12890	-2.325	0.020089	*
Yes	1.07E+00	0.15560	6.848	7.47E-12	***
Education *(ordered factor)*					
Currently in high school	-2.78E-01	0.32720	-0.849	0.395855	
High school GED	4.14E-01	0.28560	1.450	0.147127	
Currently in 2-year college	-3.16E-01	0.26250	-1.204	0.228457	
2-year college degree	7.46E-02	0.30470	0.245	0.806609	
Currently in 4-year college	-2.00E-01	0.31380	-0.638	0.523738	
4-year college degree	-8.51E-03	0.22760	-0.037	0.970168	
Currently in post-graduate degree	3.11E-01	0.20070	1.549	0.121348	
Post-graduate degree	-3.41E-03	0.19390	-0.018	0.985963	
Race or Ethnicity					
American Indian or Alaskan Native (alone)	-2.03E-01	0.56010	-0.362	0.717402	
Asian	-4.09E-02	0.17690	-0.231	0.817135	
Caucasian/White	1.03E-01	0.13340	0.769	0.442122	
Hispanic or Latino	4.93E-01	0.19440	2.533	0.011296	*
Middle-Eastern	4.07E-01	0.50570	0.804	0.421302	
Mixed	3.63E-01	0.21830	1.662	0.096605	.
Native Hawaiian or Pacific Islander	-5.28E-01	0.64200	-0.822	0.410927	
Southeast Asian	-2.03E-01	0.85360	-0.238	0.811991	

Signif. Codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.'

13.1.4 Stated Preference & Willingness to Pay

Table 22: Stated Preference and Willingness to Pay

Call:

```
glm(formula = Decision ~ Purpose2 + Cost + Distance + Familiarity + Commute_Distance2 +
  Age_Continuous + Gender + Income + Education3 + Race.Ethnicity + City, family = "binomial",
  data = mydata2)
```

Deviance Residuals:

Min	1Q	Median	3Q	Max
-2.408	-0.7959	-0.4851	0.9377	2.8575

	Estimate	Std. Error	Z Value	Pr(>|z|)	
Intercept	1.25E+00	1.41E-01	8.838	2.00E-16	***
Covariate variables					
UAM Trip Cost	-2.13E-02	0.00070	-30.311	2.00E-16	***
UAM Trip Distance	1.80E-02	0.00127	14.099	2.00E-16	***
Commute Distance	1.00E-02	0.00191	5.240	0.000000	***
Age	-2.27E-02	0.00158	-14.337	0.000000	***
Income	1.97E-06	0.00000	4.159	0.000032	***
Factor variables					
Trip Purpose					
Going to Work/School	-7.15E-01	0.05906	-12.109	0.000000	***
Recreational	-1.41E-01	0.06224	-2.269	0.023258	*
Familiarity					
No	-2.92E-01	0.07171	-4.069	0.000047	***
Yes	8.72E-01	0.08154	10.687	0.000000	***
Gender (Male)	2.95E-01	0.04916	6.005	1.91E-09	***
Education *(ordered factor)*					
Currently in high school	-3.01E-01	0.16990	-1.773	0.076245	.
High school GED	1.16E-01	0.14220	0.818	0.413451	
Currently in 2-year college	-1.24E-01	0.13370	-0.924	0.355449	
2-year college degree	-4.20E-01	0.16490	-2.545	0.010916	*
Currently in 4-year college	-2.45E-01	0.17180	-1.425	0.154044	
4-year college degree	-3.89E-01	0.12590	-3.088	0.002012	**
Currently in post-graduate degree	-1.17E-02	0.10680	-0.110	0.912769	
Post-graduate degree	-2.86E-01	0.10280	-2.784	0.005364	**
Race or Ethnicity					
American Indian or Alaskan Native (alone)	3.38E-01	0.29760	1.137	0.255585	
Asian	-9.68E-02	0.10000	-0.967	0.333358	
Caucasian/White	-1.47E-01	0.07229	-2.039	0.041491	*
Hispanic or Latino	-3.07E-02	0.10480	-0.293	0.769764	
Middle-Eastern	6.97E-01	0.26780	2.603	0.009239	**
Mixed	1.26E-01	0.11540	1.094	0.273777	
Native Hawaiian or Pacific Islander	-1.10E+00	0.45770	-2.398	0.016498	*
Southeast Asian	-9.08E-01	0.49780	-1.824	0.068197	.
City					
Los Angeles	1.75E-01	0.07483	2.338	0.019388	*
New York City	6.45E-02	0.07732	0.834	0.404043	
San Francisco Bay Area	-3.03E-01	0.08062	-3.758	0.000171	***
Washington, D.C.	-1.10E-02	0.07680	-0.143	0.886545	

Signif. Codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.'

13.1.5 Weather Considerations

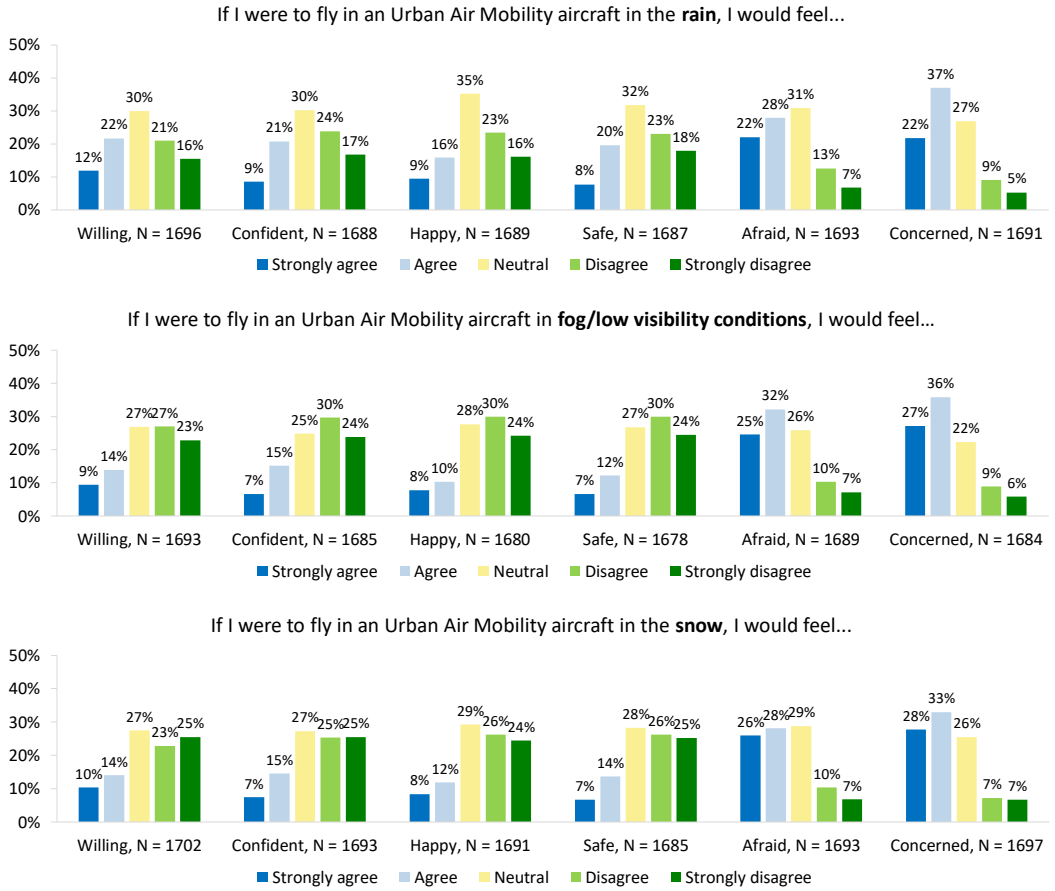


Figure 82: Perceptions of Weather

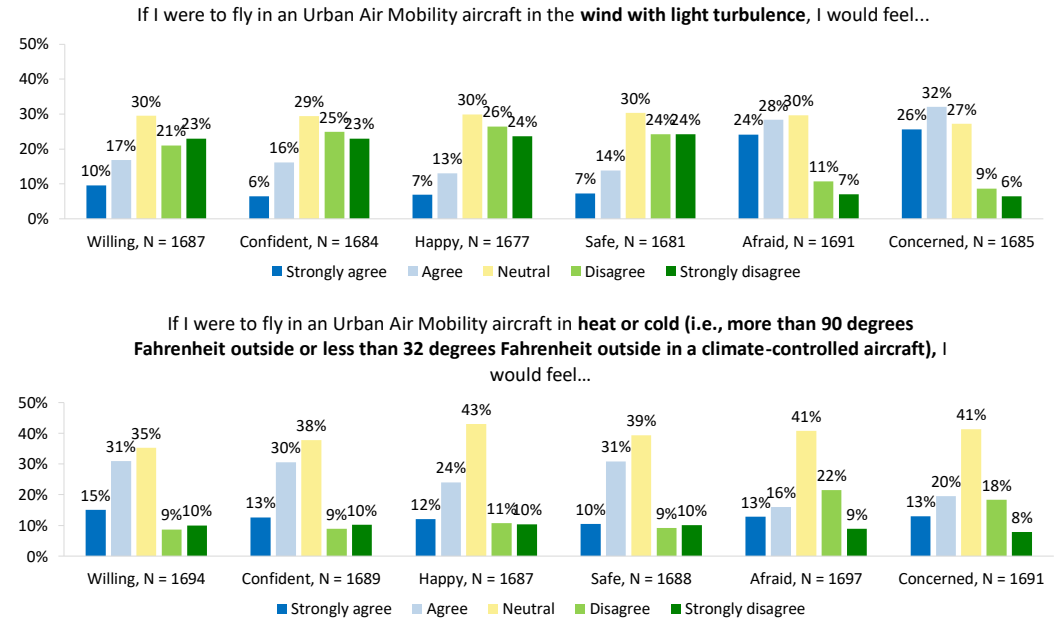


Figure 83: Perceptions of Weather (cont…)

13.1.6 Market Preferences

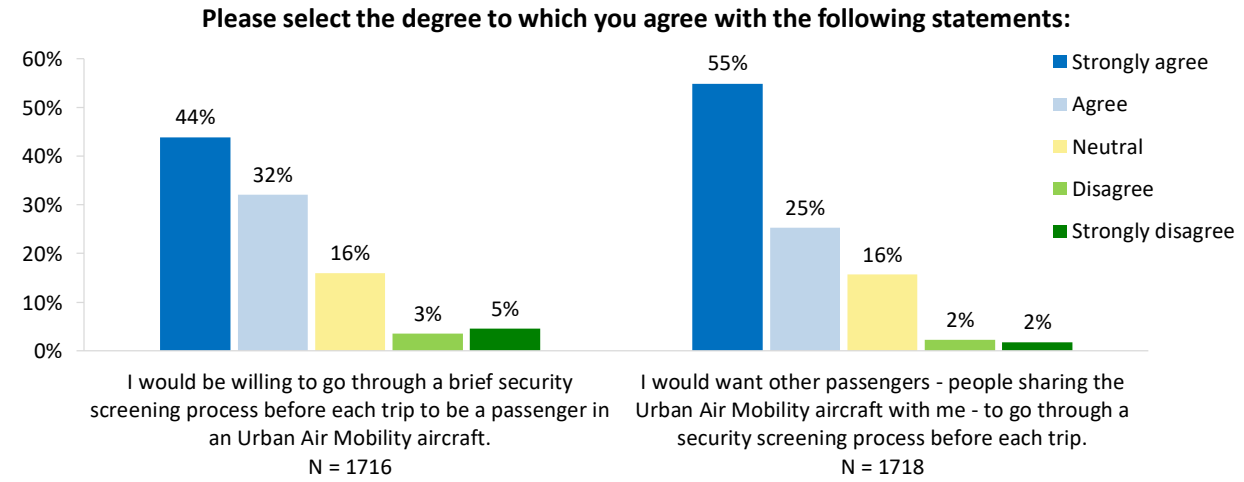


Figure 84: Security Screenings

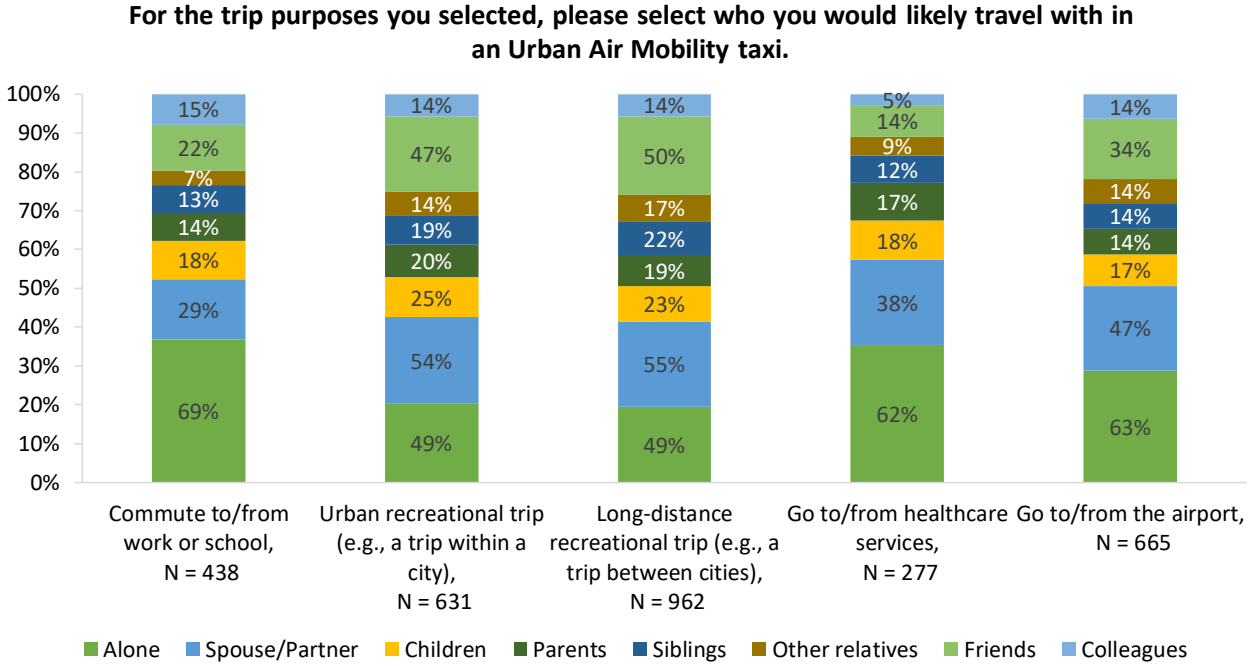


Figure 85: Likely Travel Partners

As automation becomes an increasingly prevalent feature of transportation, it is likely that UAM will exist alongside an automated vehicle future. As such, we aimed to evaluate the extent to which respondents would use UAM in an altered transportation landscape. Respondents were introduced to the concepts of automated vehicles (AVs) and shared automated vehicles (SAVs) through short descriptions, as follows:

*"**AVs** are vehicles that move passengers with some level of automation that assists or replaces human control. **Shared AVs** are automated vehicles that are shared among multiple users and can be summoned on-demand similar to ridesourcing (Uber/Lyft) or can operate a fixed-route service like a bus."*

Next, we asked respondents whether they would prefer to use an AV or SAV over a UAM aircraft for the trip purposes they had already selected for use. Generally, respondents preferred UAM aircraft for long-distance trips and going to/from the airport, while they preferred AVs for commuting and urban recreational

trips. Across the cities, preferences for UAM vs. AVs varied, as seen in Figure 86 below. Respondents in Los Angeles appeared to be more open to future technologies, as there were far fewer neutral responses. Respondents in New York City expressed a slight preference for using UAM for healthcare trips, perhaps due to the location of health services within the cityscape or traffic concerns. The other cities were either evenly split or preferred AV for healthcare trips.

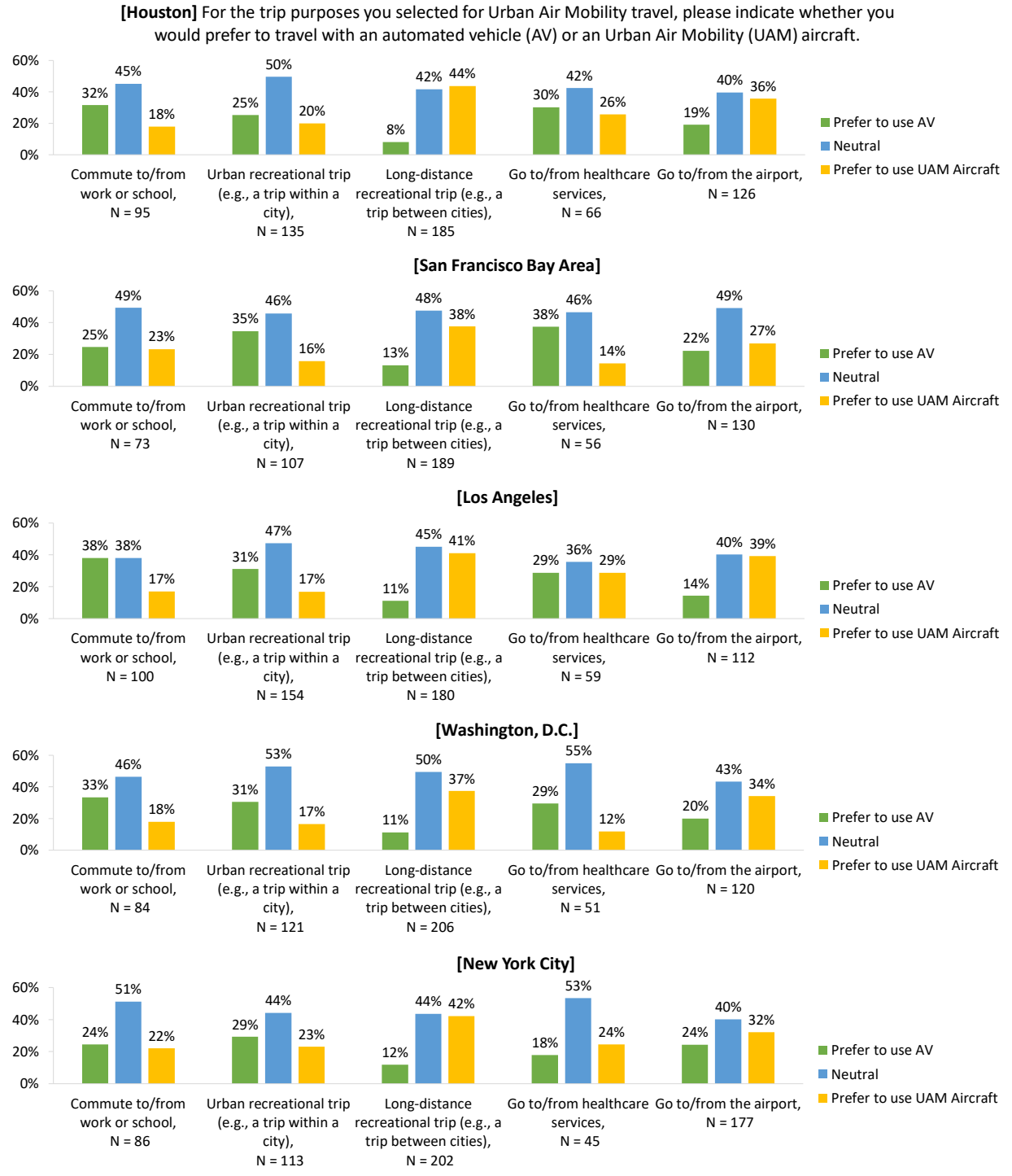


Figure 86: AV vs. UAM Travel

Regarding SAVs, respondents were slightly less likely to prefer SAVs over UAM aircraft than they were to prefer AVs over UAM aircraft (see Figure 87 below). Respondents generally preferred UAM for long-distance travel and trips to/from the airport, while preferring SAVs for commuting and urban recreational trips. However, the respondents from the San Francisco Bay Area tended to be less favorable to SAVs than respondents from the other four cities. In San Francisco, UAM was preferred over SAVs for commuting and there was very little preference between the two modes for urban recreational trips.

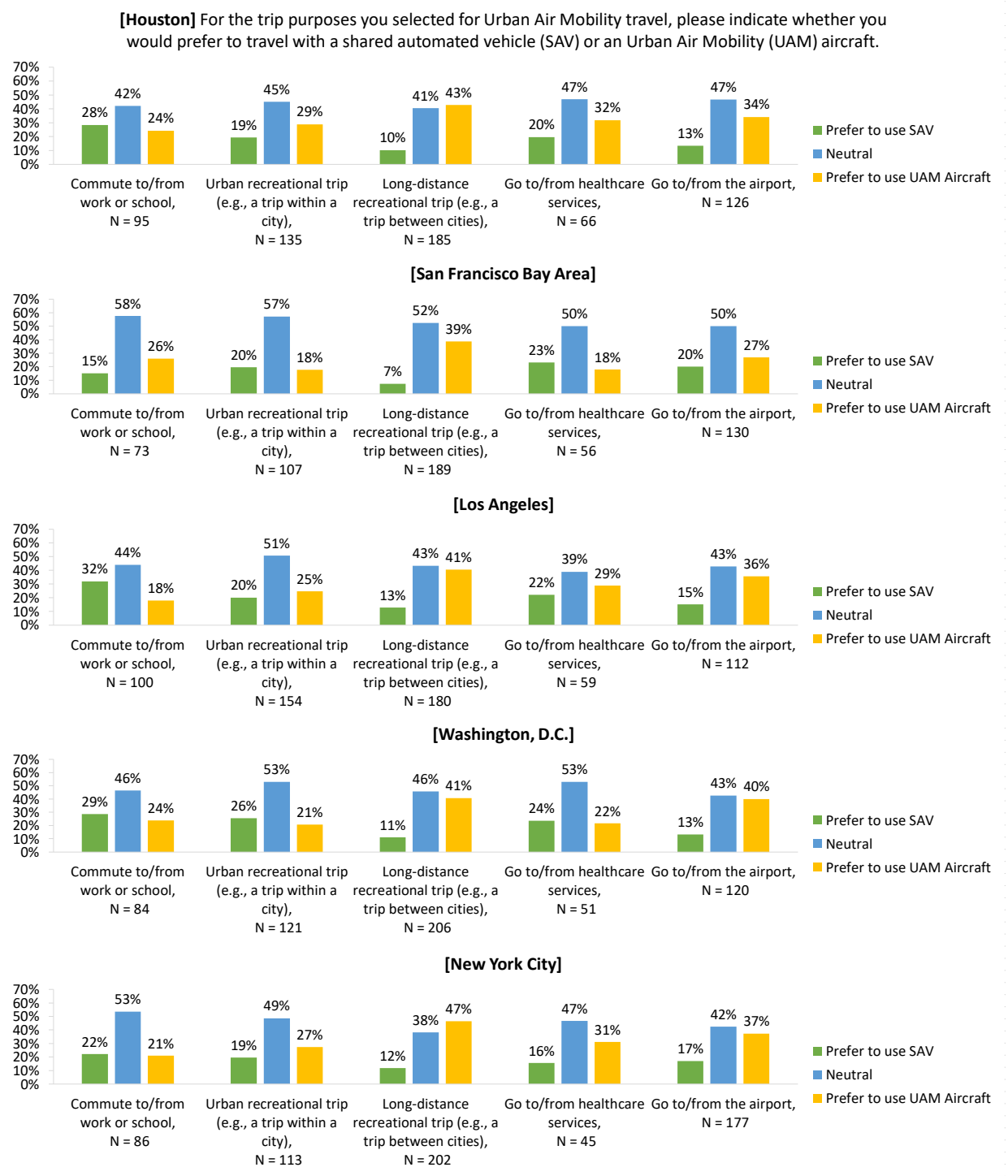


Figure 87: SAV vs. UAM Travel

Next, we asked several questions related to vertiports (specified landing/takeoff locations for UAM aircraft). Future UAM users will most likely need to travel to vertiports to use the service, and users will most likely take multimodal trips which require travel to access a UAM aircraft. We asked survey respondents whether they would be willing to travel to a vertiport, how much they would be willing to pay to travel to a vertiport, and how much time they would be willing to spend traveling to the vertiport. An additional question probed the preferred transportation mode that each respondent would use to access the vertiport. The results of these questions are presented in Figure 88 to 89, as well as Table 23.

Approximately half of the respondents were willing to travel to the vertiport; an additional 31% of respondents indicated that they might be willing to travel to the vertiport. Women were more hesitant to travel to a vertiport – a slightly higher proportion of women were unwilling to travel to a vertiport and more women also indicated that they might travel to a vertiport (Figure 88). Of the respondents who were willing to use a vertiport, most were unwilling to take more than 20 to 30 minutes to travel to it (Figure 89). Likewise, most were not willing to pay more than $10 to access a vertiport (Figure 90).

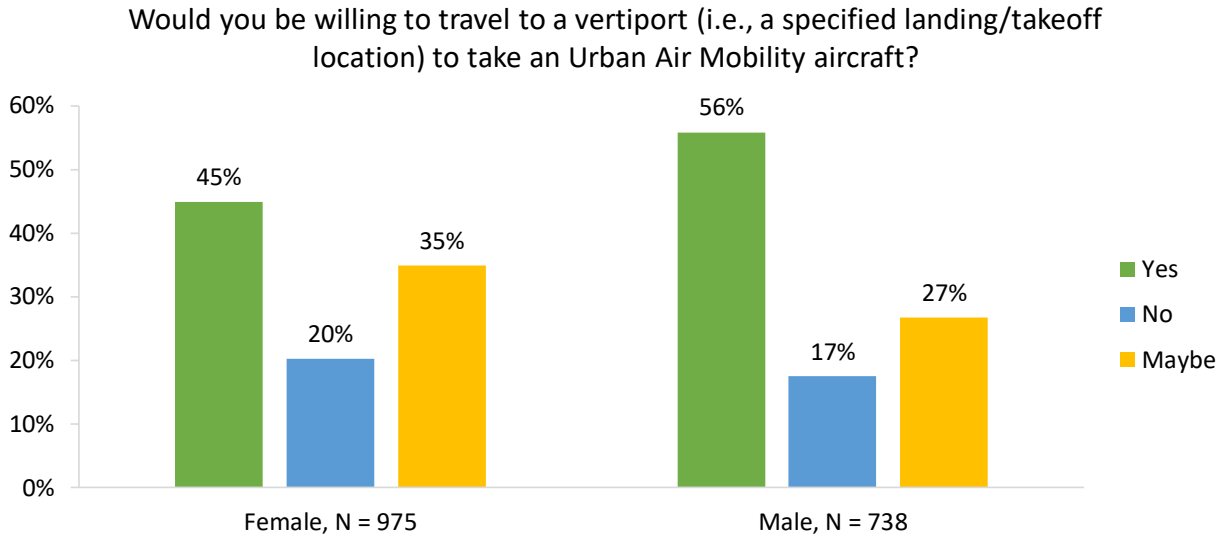


Figure 88: Willingness to Use Vertiport

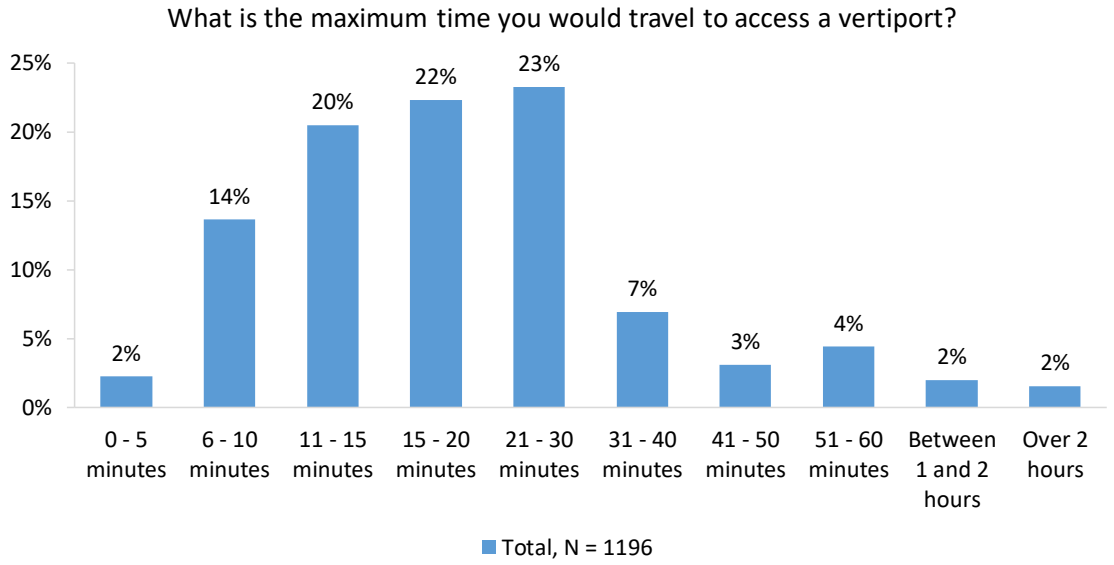


Figure 89: Time to Access Vertiport

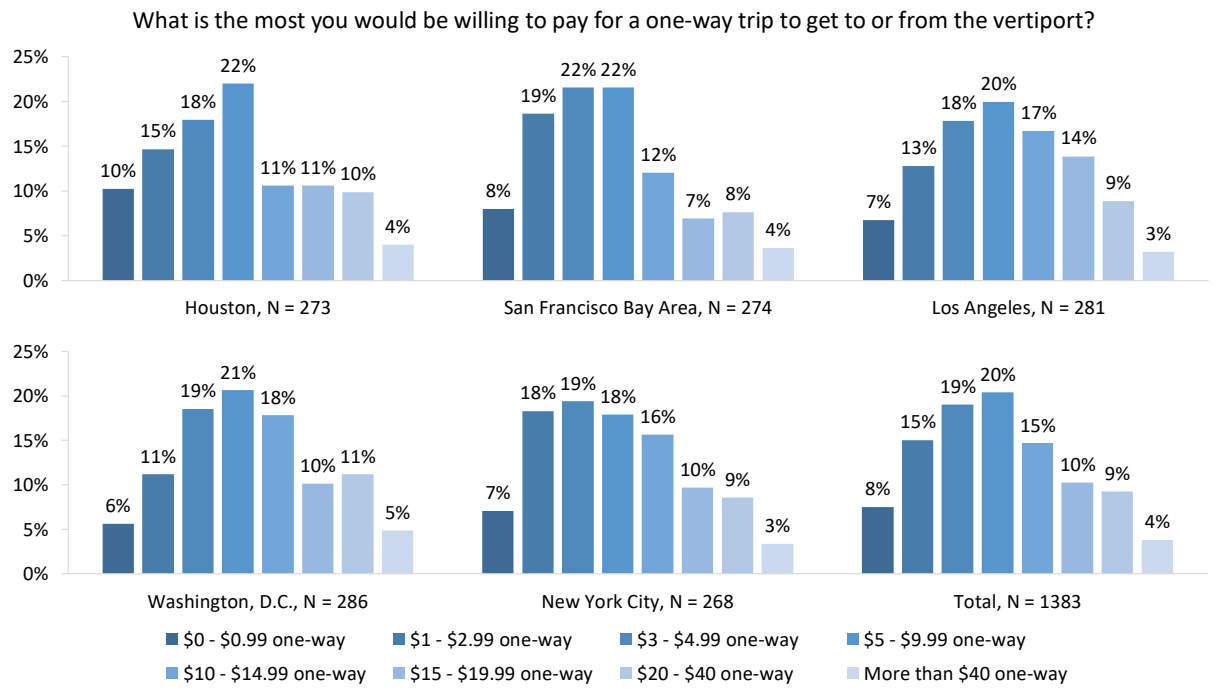


Figure 90: Cost to Access Vertiport

Most respondents would prefer to drive, take public transit, or use ridesourcing (e.g., Lyft, Uber) to access the vertiport (see Table 23). San Francisco and New York City each had 10% of respondents that preferred to walk or run to access a vertiport, while Los Angeles had around 7% of respondents preferring carsharing (e.g., Zipcar, car2go).

Table 23: Preferred Modes for Vertiport Access

	Total, N = 1380	Houston, N = 273	San Francisco Bay Area, N = 274	Los Angeles, N = 278	Washington, D.C., N = 287	New York City, N = 267
Driving	39%	58%	32%	46%	42%	15%
Public Transit	25%	12%	28%	17%	28%	42%
Ridesourcing	16%	16%	18%	20%	11%	15%
Taxi	3%	1%	4%	1%	2%	9%
Bicycle	1%	0%	1%	0%	0%	1%
Bike Sharing	0%	0%	0%	0%	1%	0%
Car Sharing	1%	1%	0%	0%	1%	1%
Automated Vehicle	4%	5%	3%	7%	5%	3%
Shared Automated Vehicle	1%	1%	1%	1%	0%	1%
Walk/Run	7%	3%	10%	5%	6%	10%
Other	3%	2%	3%	4%	5%	3%

Many of the respondents (52% across the sample population) were not interested in owning a personal UAM aircraft; however, 17% of respondents were interested in ownership. Men were more interested in owning a UAM aircraft than women (21% for men vs. 13% for women). We also explored whether the supply of UAM aircraft and pilots could be augmented through peer-to-peer (P2P) operations. For example, would owners of UAM aircraft be willing to rent out their aircraft or transport other people (similar to services, such as Lyft and Uber)? For those who answered “yes,” “maybe,” or “I don’t know” to the question of interest in owning a personal UAM aircraft, there is high willingness to use the aircraft as part of a larger fleet service (e.g., Lyft, Uber). Approximately 44% of the sample respondents were willing to rent out their personal UAM aircraft for use by others. Los Angeles had a particularly high willingness to participate in shared mobility services – around 55% of those willing to own an aircraft were willing to also rent it out to others (i.e., a P2P

service model). This suggests that perhaps there may be room for P2P operations with UAM aircraft. However, respondents were not as interested in fractional ownership (i.e., shared ownership of a UAM among individuals). Only 20% of the sample respondents were willing to share ownership of a UAM aircraft.

In order for P2P markets to be viable, licensed pilots and people willing to fly UAM aircraft are necessary. The respondents were asked if they would be willing to fly a UAM aircraft, and approximately one in five respondents were willing. Los Angeles had an even higher percentage of respondents who were willing to fly a UAM aircraft at 30%. However, the survey population was heavily skewed toward those with pilot's licenses. Approximately one in five of the survey respondents claimed to possess a pilot's license, which is much higher than the national average. As of 2017, only 0.2% of U.S. residents were active certified pilots (FAA, 2018).

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13.2 Appendix 2 – Weather Analysis

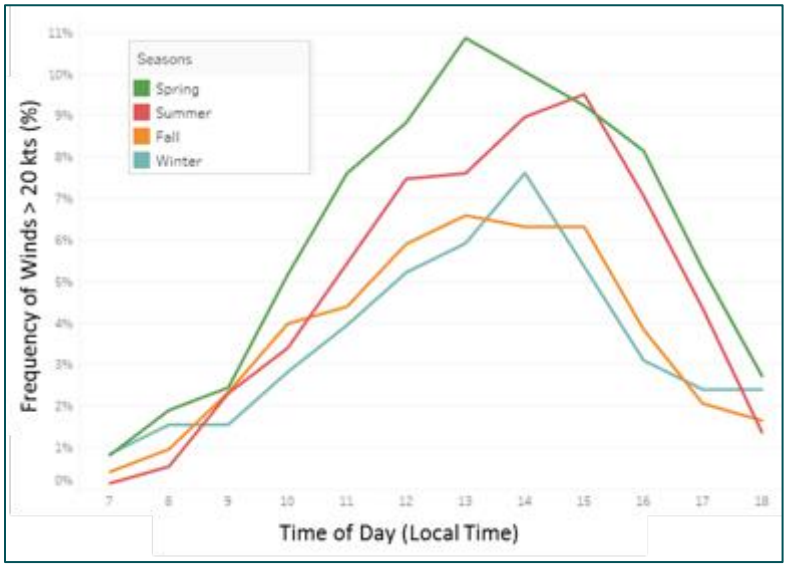


Figure 91: Time series of frequency of winds above 20 kts by season in Honolulu urban area.

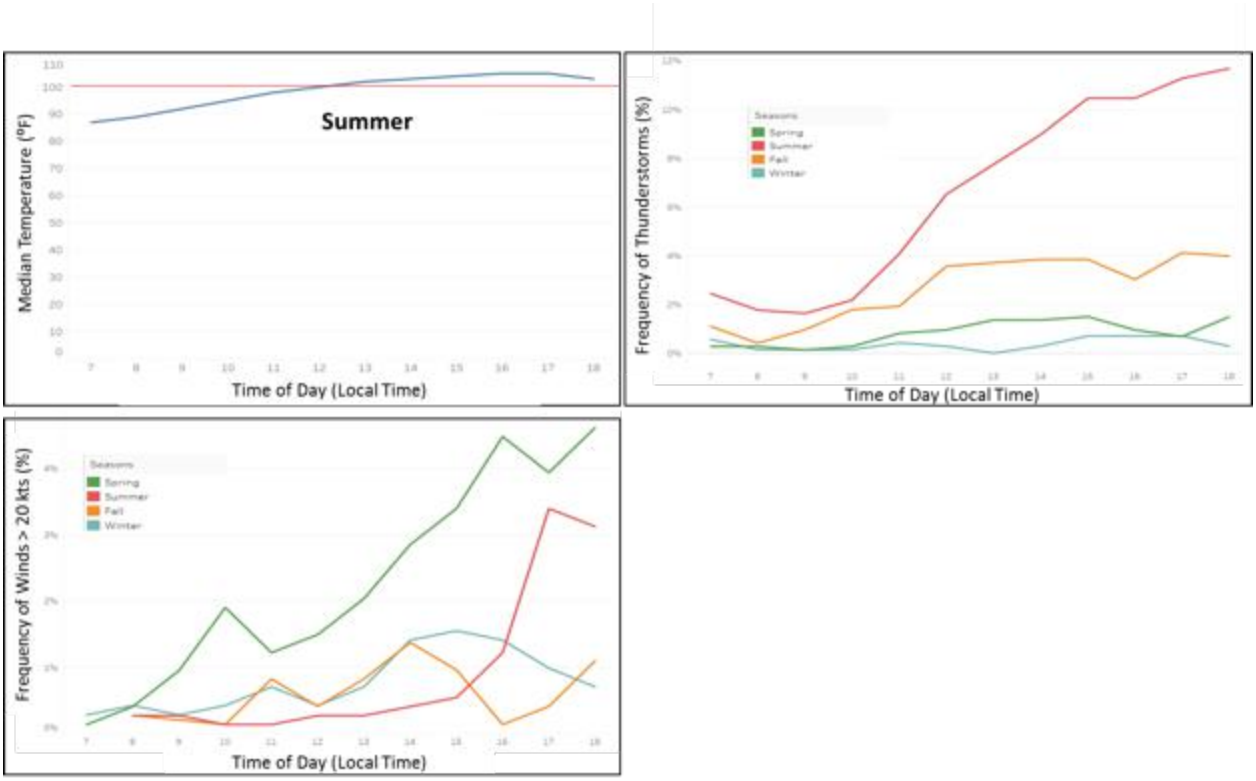


Figure 92: Time series of median temperature in summer (top left), frequency of thunderstorms by season (top right), and frequency of winds above 20 kts by season (bottom left) in Phoenix urban area.

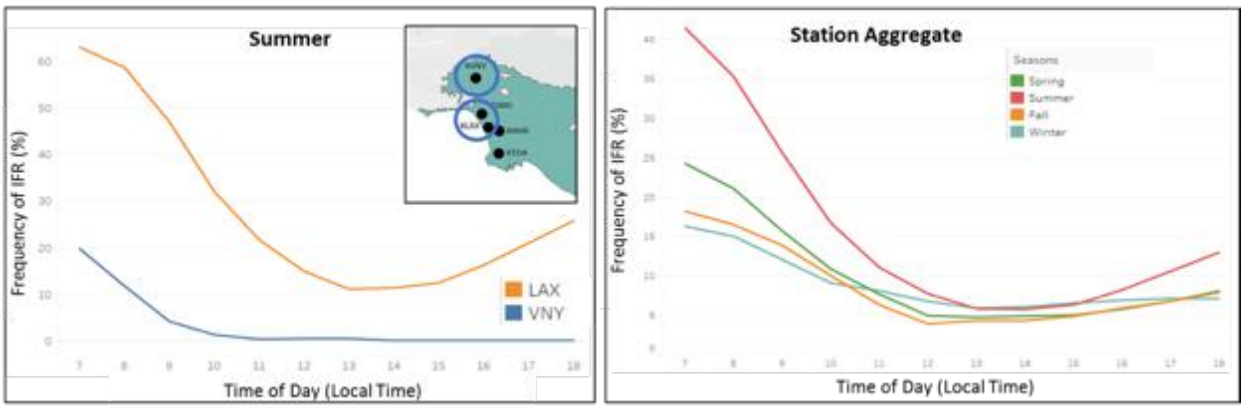


Figure 93: Time series of frequency of IFR conditions in summer at LAX and VNY (left) and in aggregate by season in Los Angeles urban area.

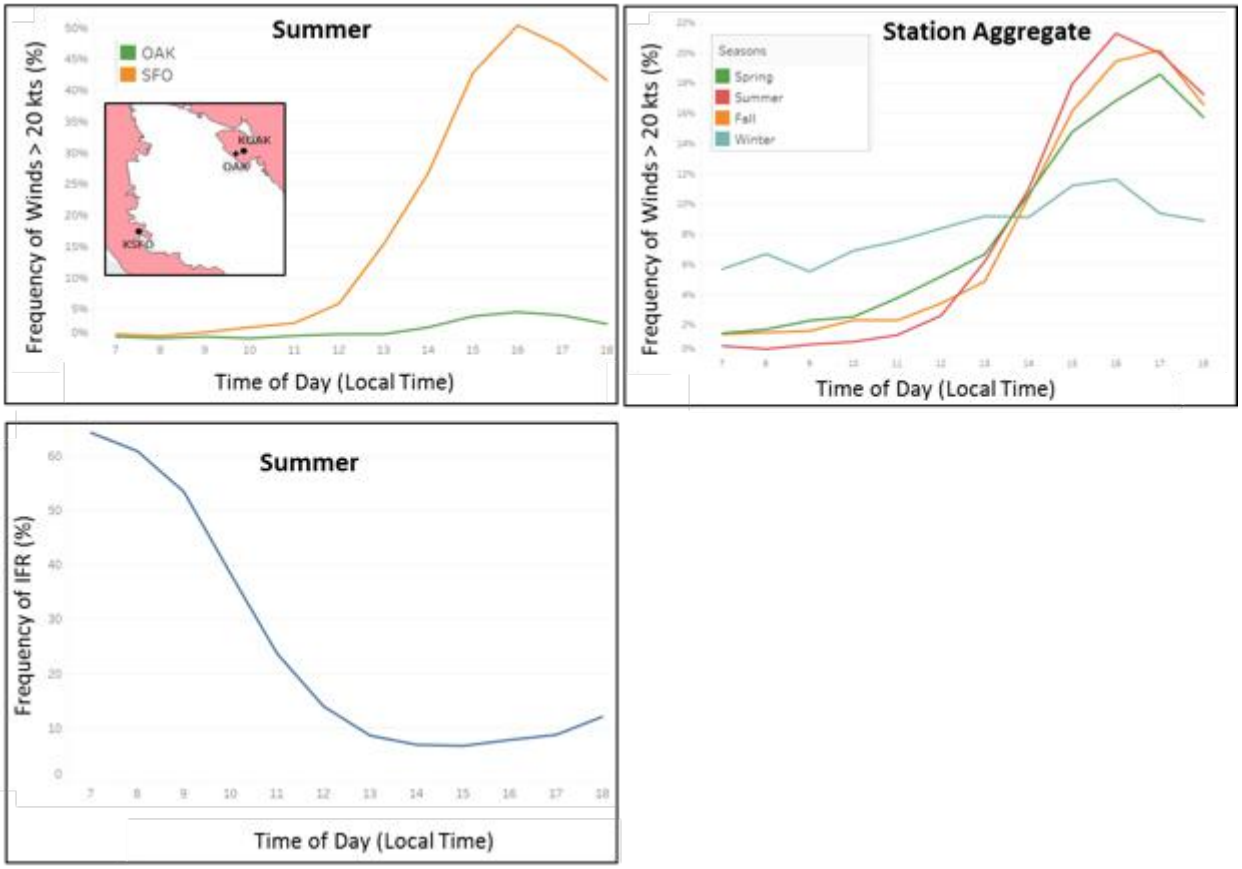


Figure 94: Time series of frequency of winds above 20 kts in summer at OAK and SFO (top left), station aggregate by season (top right), and frequency of IFR conditions in summer (bottom left) in San Francisco urban area.

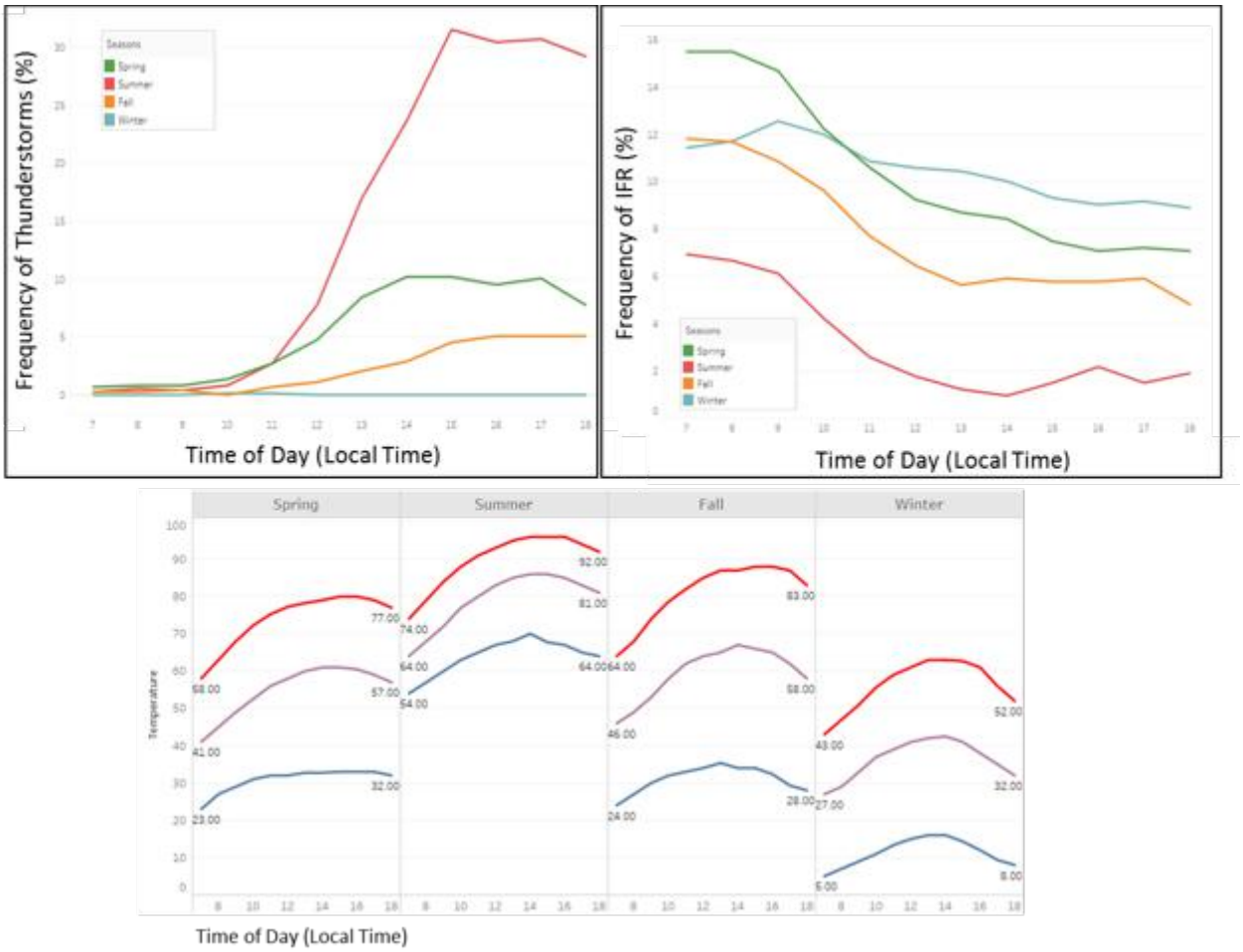


Figure 95: Time series of frequency of thunderstorms by season (top left), frequency of IFR conditions by season (top right), and 5th percentile (blue line), median (purple line), and 95th percentile (red line) temperature by season (bottom) in Denver urban area.

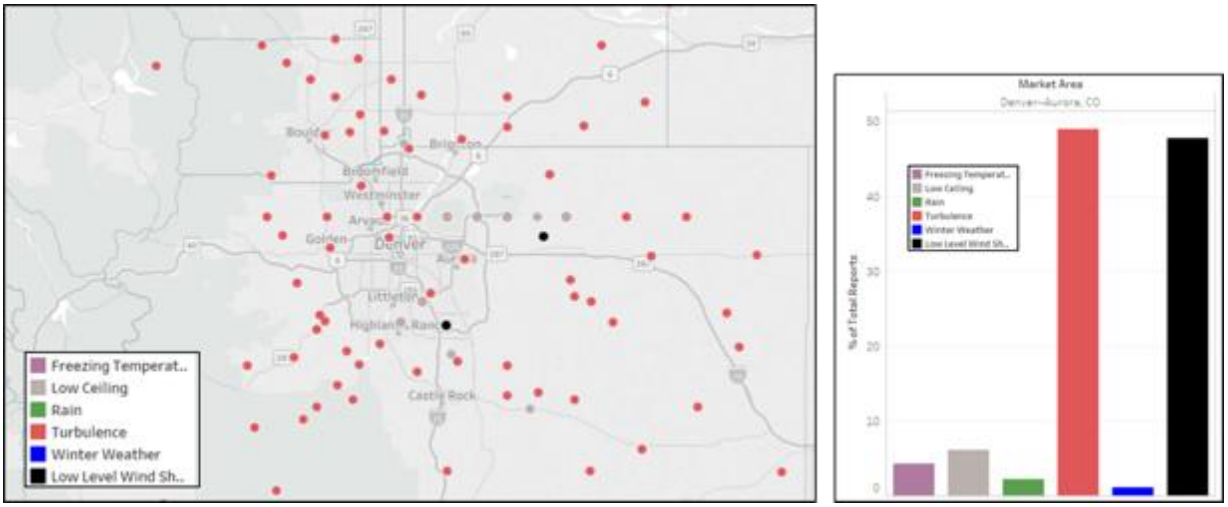


Figure 96: Spatial distribution of PIREPs (left) and percentage of total reports by reported condition across historical period in Denver urban area.

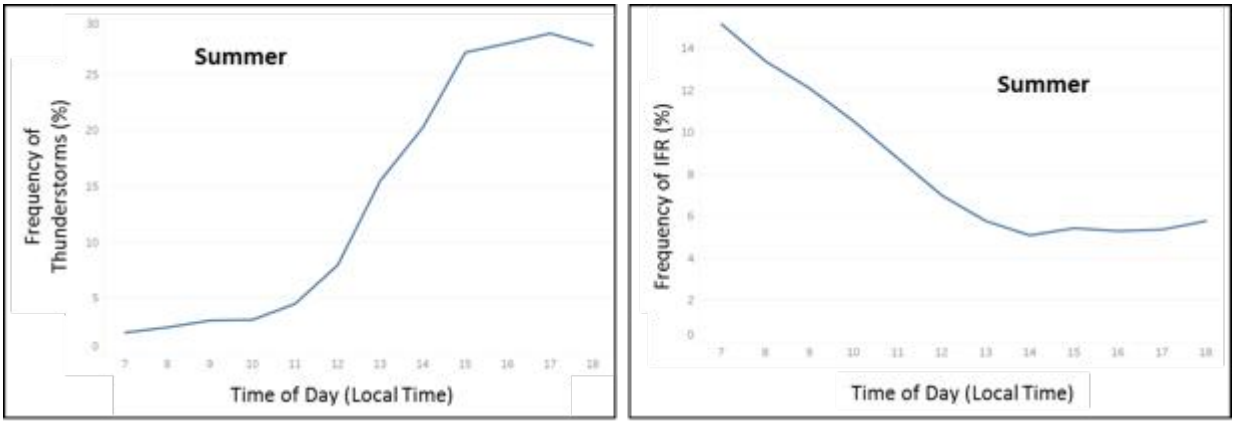


Figure 97: Time series of frequency of thunderstorms in summer (left) and frequency of IFR conditions in summer (right) in Washington, D.C. urban area.

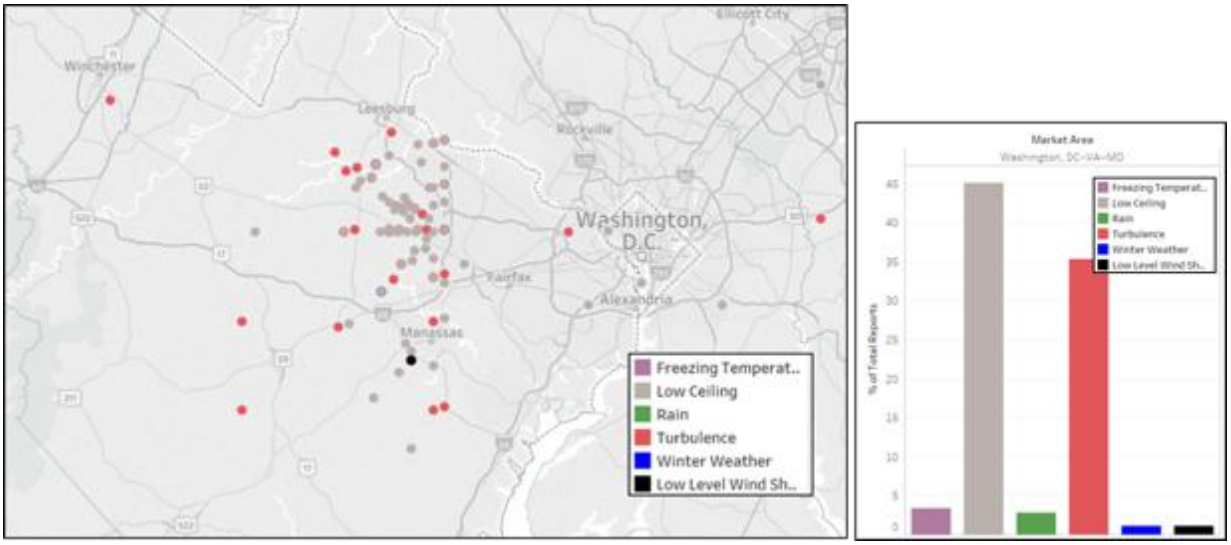


Figure 98: Spatial distribution of PIREPs (left) and percentage of total reports by reported condition across historical period in Washington, D.C. urban area.

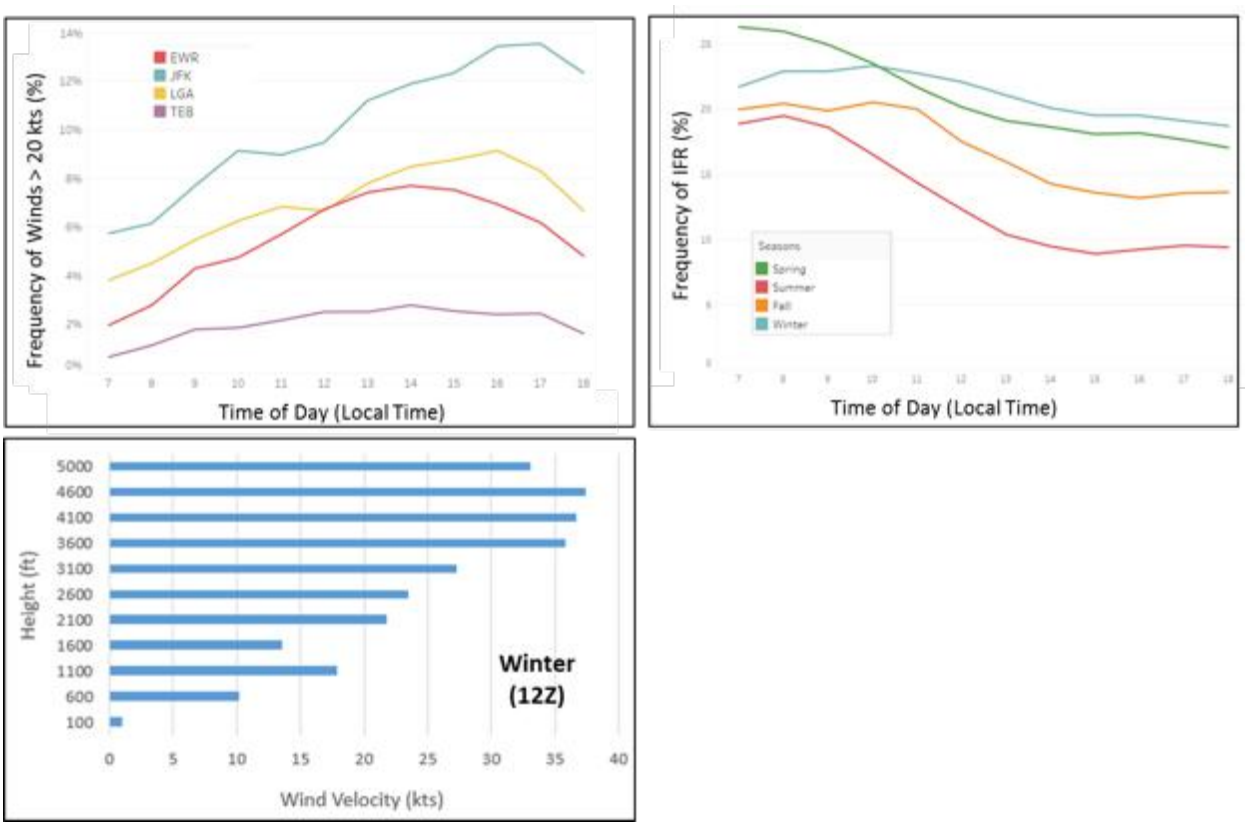


Figure 99: Time series of frequency of winds above 20 kts in winter by METAR location (top left), frequency of IFR conditions by season (top right), and vertical distribution of wind speed during winter morning in New York urban area.

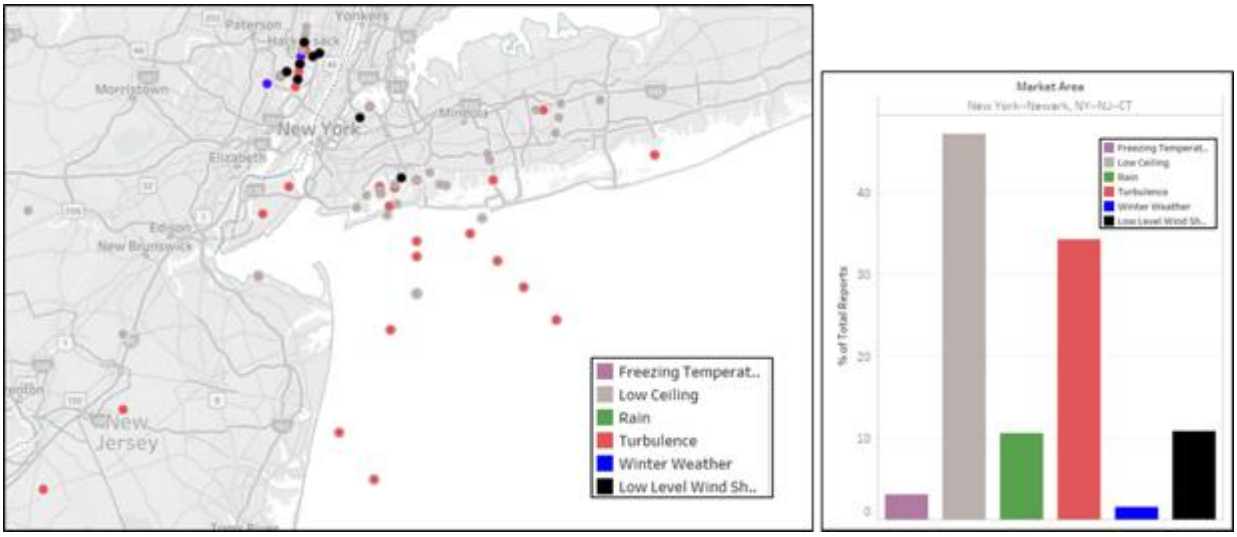


Figure 100: Spatial distribution of PIREPs (left) and percentage of total reports by reported condition across historical period in New York urban area.

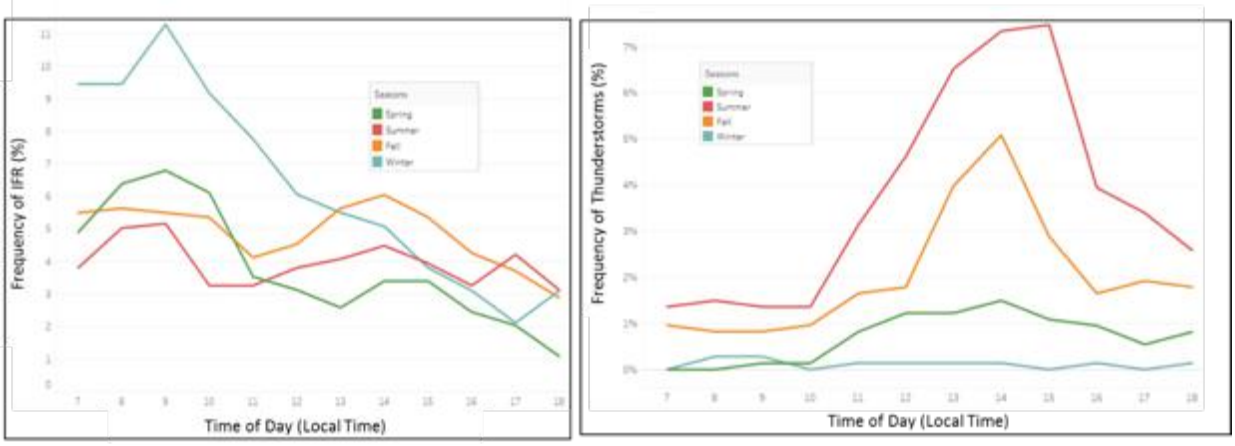
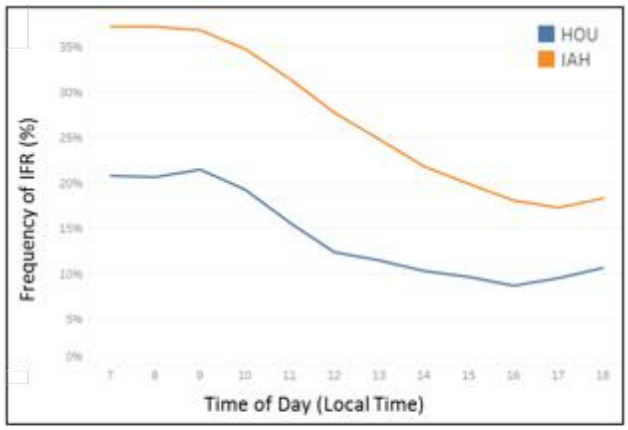


Figure 101: Time series of frequency of IFR conditions by season (left) and frequency of thunderstorms by season (right) in Miami urban area.



	Fall	Spring	Summer	Winter
TMax	99.00	97.00	105.00	86.00
TMin	32.00	28.00	70.00	23.00
Temp Range	67.00	69.00	35.00	63.00
Temp95P	90.00	86.00	96.00	77.00
Temp50P	78.00	75.00	88.00	60.00
Temp5P	54.00	56.00	77.00	39.00

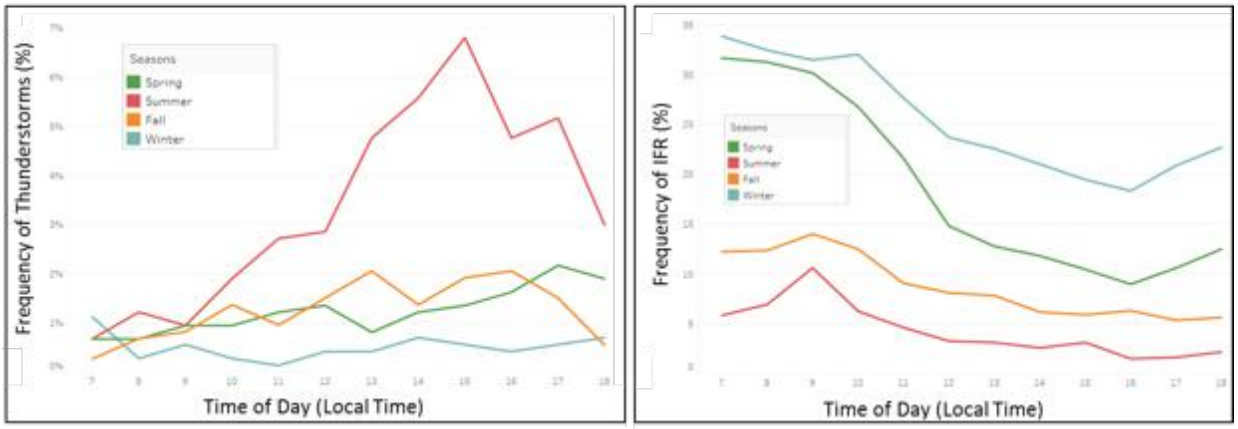


Figure 102: Time series of frequency of IFR conditions in winter at HOU and IAH (top left), frequency of thunderstorms by season (bottom left), frequency of IFR conditions in aggregate by season (bottom right), and temperature statistics by season in Houston urban area.

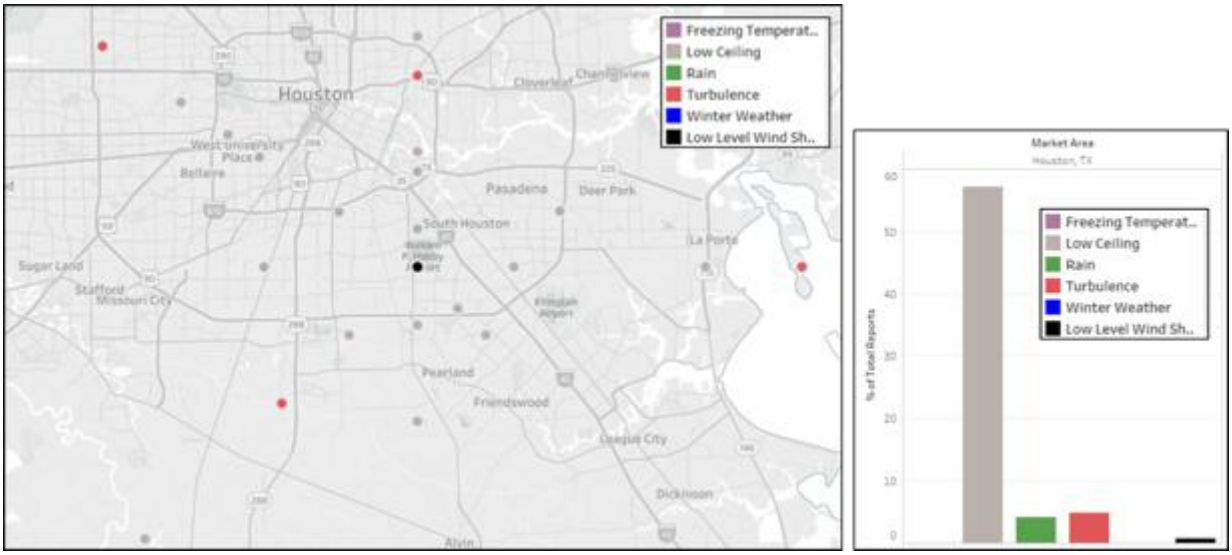


Figure 103: Spatial distribution of PIREPs (left) and percentage of total reports by reported condition across historical period in Houston urban area.

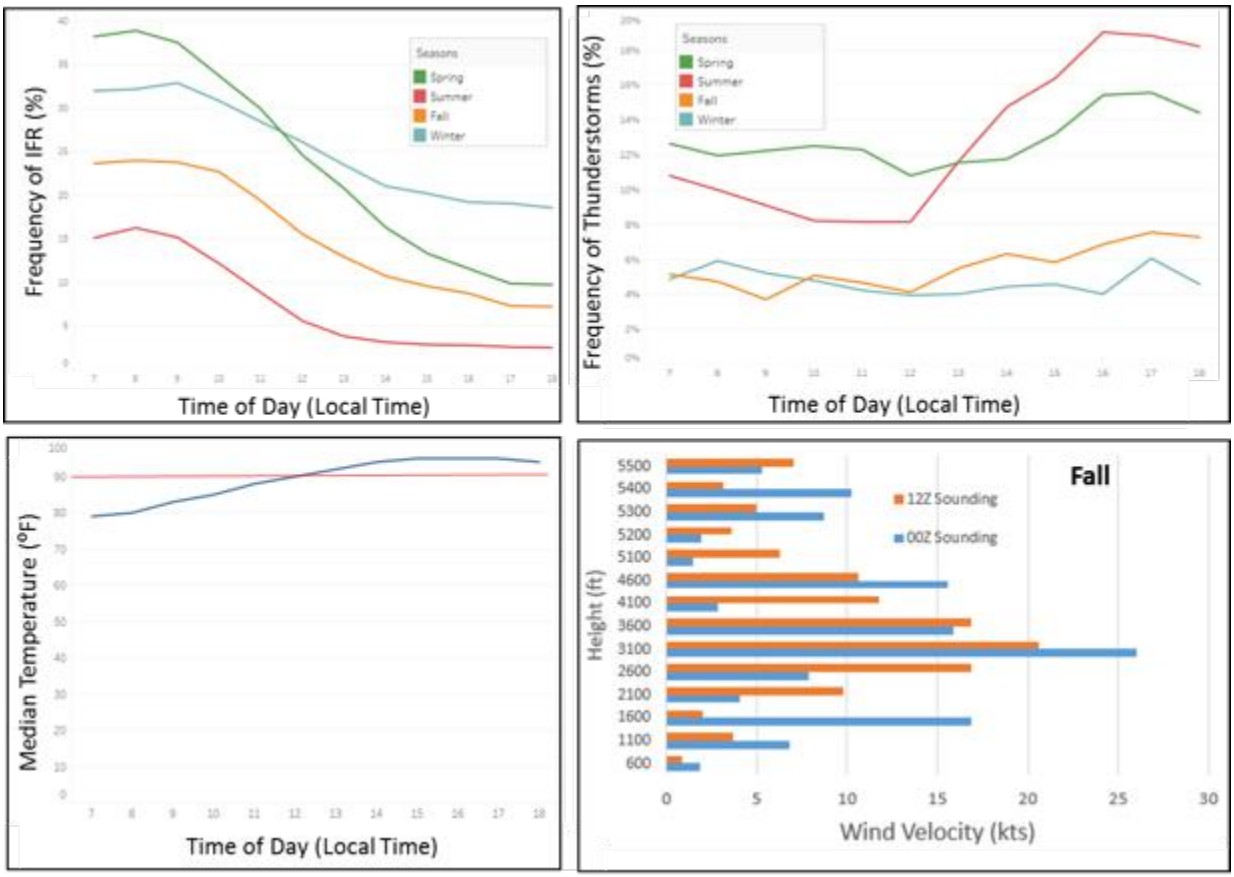


Figure 104: Time series of frequency of IFR conditions by season (top left), frequency of thunderstorms by season (top right), median temperature in summer (bottom left), and vertical distribution of wind speed during fall at both 12Z and 00Z in Dallas urban area.

13.3 Appendix 3 – Market Analysis

NON-EXHAUSTIVE

MULTIROTOR MARKET OVERVIEW

Manufacturer	Product	Technical Specifications	
Workhorse (Photo Source: http://workhorse.com/surefly)	SureFly	Passengers Range MTOW Cruise Speed Cost Timeline	2 70 mi 1500 lbs. 50 mph $200,000 First flight in April 2018
Astro (Photo Source: https://flyastro.com/)	Passenger Drone	Passengers Range MTOW Cruise Speed Cost Timeline	2 20 mi 800 lbs. 50 mph $150,000 First flight in August 2017
Ehang (Photo Source: http://www.ehang.com/ehang184/gallery/)	Ehang 184	Passengers Range MTOW Cruise Speed Cost Timeline	1 10 mi 795 lbs. 50 mph $250,000 Flight testing in 2016-2017
VRCO (Photo Source: http://www.vrco.co.uk/)	NeoXCraft	Passengers Range MTOW Cruise Speed Cost Timeline	2 210 mi 1600 lbs. 50 mph $2M NA

TILT ROTOR MARKET OVERVIEW

Manufacturer	Product	Technical Specifications	
Bartini (Photo Source: https://bartini.aero/)	Flying Car	Passengers Range MTOW Cruise Speed Cost Timeline	4 93 mi 2425 lbs. 150 mph $120,000 Fully functioning by 2020
Joby Aviation (Photo Source: http://www.jobyaviation.com/S2ConceptualDesignIAA1.pdf)	S2 EVOTL	Passengers Range MTOW Cruise Speed Cost Timeline	2 200 mi 2000 lbs. 150 mph $200,000 First flight in 2018
EVA (Photo Source: http://evtol.news/aircraft/eva-x01/)	XO1	Passengers Range MTOW Cruise Speed Cost Timeline	2 156.25 mi 2000lbs 150 mph $297,619 Testing in 2019
XTI (Photo Source: http://www.xtiaircraft.com/the-a-team/)	TriFan 600	Passengers Range MTOW Cruise Speed Cost Timeline	6 1377 mi 5300 lbs. 150 mph $6.5M First flight 2019

LIFT AND CRUISE MARKET OVERVIEW

Manufacturer	Product	Technical Specifications	
Napoleon Aero (Photo Source: http://evtol.news/aircraft/napoleon-aero-vtol/)	Napoleon Aero VTOL	Passengers Range MTOW Cruise Speed Cost Timeline	4 62 mi 3300 lbs. 150 mph NA NA
Aurora (Photo Source: http://www.aurora.aero/evtol/)	Electric VTOL Multicopter	Passengers Range MTOW Cruise Speed Cost Timeline	2 NA 1760 lbs. 150 mph NA Expected 2020
Cartivator (Photo Source: http://cartivator.com/skydrive)	Skydrive	Passengers Range MTOW Cruise Speed Cost Timeline	2 NA mi 880 lbs. 150 mph NA NA
Skypod (Photo Source: http://evtol.news/aircraft/skypod/)	Skypod	Passengers Range MTOW Cruise Speed Cost Timeline	2 NA 1600 lbs. 150 mph NA NA

TILT DUCT MARKET OVERVIEW

Manufacturer	Product	Technical Specifications	
Lilium (Photo Source: https://lilium.com/)	Lilium Jet	Passengers Range MTOW Cruise Speed Cost Timeline	2 186 mi 1410 lbs. 150 mph NA Expected 2019
Skylys (Photo Source: http://evtol.news/aircraft/skylys-ao/)	AO	Passengers Range MTOW Cruise Speed Cost Timeline	2 93 mi 2400 lbs. 150 mph NA Expected 2018
Bell Helicopter (Photo Source: http://www.bellflight.com/company/innovation/air-taxi)	Bell Air Taxi	Passengers Range MTOW Cruise Speed Cost Timeline	4 NA 3200 lbs. 150 mph NA Expected 2020
Aurora (Photo Source: http://www.aurora.aero/lightningstrike/)	Lightning Strike	Passengers Range MTOW Cruise Speed Cost Timeline	0 NA NA 150 mph NA NA

TILT WING MARKET OVERVIEW

Manufacturer	Product	Technical Specifications	
Vimana (Photo Source: http://evtol.news/aircraft/vimana/)	Unmanned AAV	Passengers Range MTOW per seat Cruise Speed Cost per seat Timeline	4 550 mi 2300 lbs. 150 mph NA NA
Air Bus A3 (Photo Source: https://vahana.aero/welcome-to-vahana-edfa68bf2b75)	Vahana	Passengers Range MTOW per seat Cruise Speed Cost per seat Timeline	2 62 mi 1600 lbs. 150 mph NA Expected 2020
ASX (Photo Source: http://airspacex.com/mobi-2025/)	MOBi	Passengers Range MTOW Cruise Speed Cost Timeline	4 65 mi 2800 lbs. 150 mph NA Expected 2025
VerdeGo Aero (Photo Source: https://www.verdegoaero.com/)	Personal Air Taxi	Passengers Range MTOW Cruise Speed Cost Timeline	2 40 mi NA 150 mph NA Expected 2020

COMPOUND HELICOPTER MARKET OVERVIEW

Manufacturer	Product	Technical Specifications
Hop Flyt (Photo Source: https://hopflyt.com)	Hop Flyt	Passengers Range MTOW per seat Cruise Speed Cost Timeline

CONVENTIONAL HELICOPTER MARKET OVERVIEW

Manufacturer	Product	Technical Specifications	
Robinson (Photo Source: https://robinsonheli.com/)	R22	Passengers Range MTOW per seat Cruise Speed Cost Timeline	2 287.5 mi 1370 lbs. 100 mph $300,000 Widely Available
Robinson (Photo Source: https://robinsonheli.com/)	R44	Passengers Range MTOW per seat Cruise Speed Cost Timeline	4 343.75 mi 2500 lbs. 100 mph $450,000 Widely Available
Carter (Photo Source: http://www.cartercopters.com/)	Cartercopter	Passengers Range MTOW Cruise Speed Cost Timeline	6 690 mi 2500 lbs. 100 mph NA NA

Figure 105: Technical specifications of select vehicles (source: eVTOL News)

13.3.1 Structure of Cost Modeling

Cost models were applied to six types of eVTOLs in 1-5 seat configuration. In the first few years of operation, there is an on-board pilot to operate the aircraft. Pilot occupies one seat, therefore, each eVTOL has one less seat available for passengers. Hence, 1-seat aircraft are assumed to be unavailable. For a certain seat category, cost per passenger mile (or vehicle mile) is calculated for each aircraft type separately. A median value is then calculated from the cost numbers of all six aircraft type that represents cost per passenger mile (or vehicle mile) for that seat category.

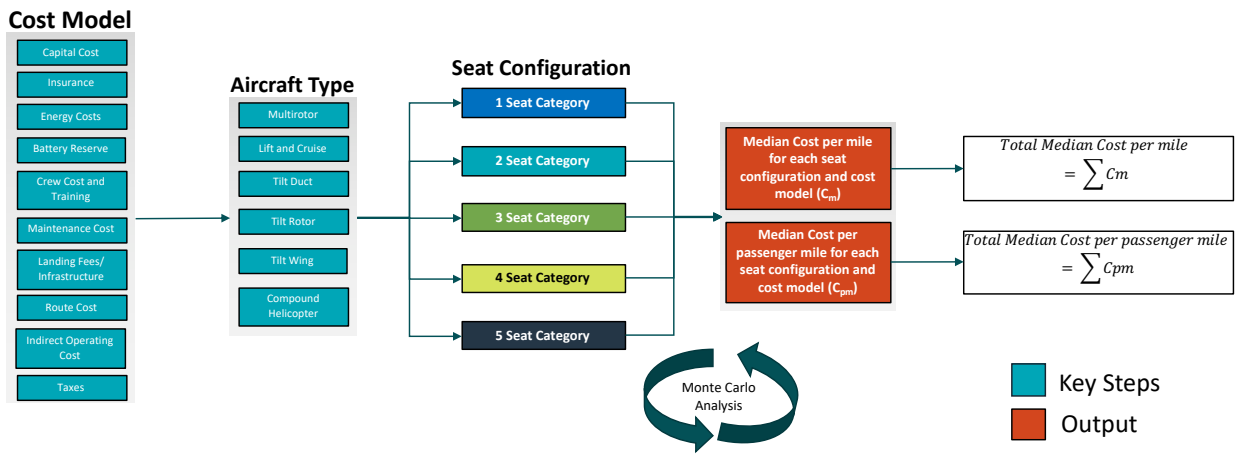


Figure 106: Structure of Cost Modeling

13.3.2 Capital and Insurance Cost Model

There are 100+ aircraft designs proposed around the world to serve urban Air Taxi and Airport Shuttle market. Our analysis assumes that each of the aircraft type may need to be priced similarly to serve the same market.

We developed a relationship between aircraft price per seat and MTOW per seat through regression analysis of the available price data as shown in the previous slides. Our analysis assumes that MTOW and aircraft price varies linearly with the number of seats (as typically observed in commercial aviation)

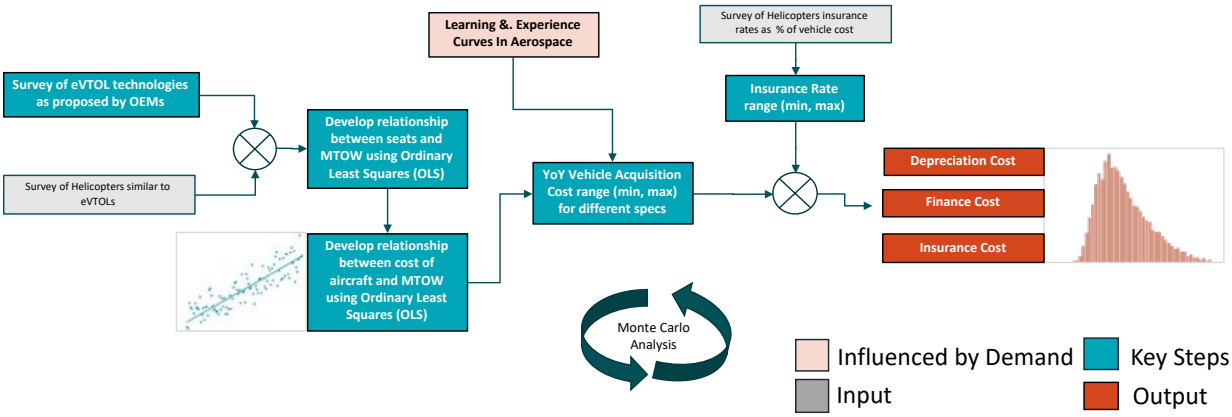


Figure 107: Capital and Insurance Cost Model

Aircraft price per seat and MTOW per seat developed through regression analysis of the available data. Our analysis assumes that MTOW and Aircraft Price varies linearly with the number of seats (as typically observed in commercial aviation)

Payload is expected to be 15-25% of aircraft weight which translates to 1000 lbs. per seat (assuming an average of 200 lbs. per passenger). However, we calculate MTOW for each aircraft class using publicly available data sources. Figure shows MTOW range for each aircraft class used in this study.

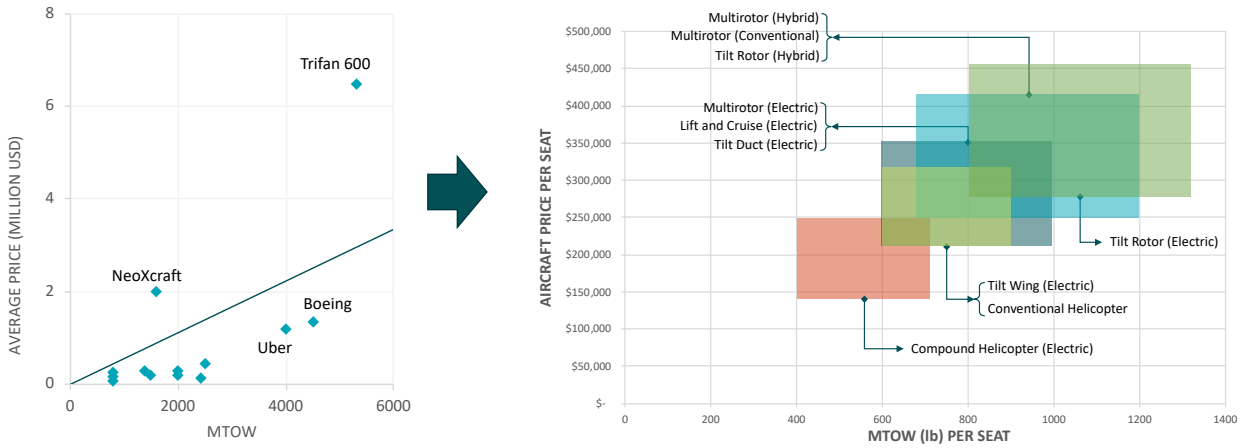


Figure 108: Aircraft Price per Seat

ASSUMPTIONS

Parameter	Min	Max	Source
Vehicle Life (flight hours)	12000	25000	SAG Interviews[1] Cirrus SR20 Cessna 350
Depreciation Rate (%)	5%	10%	BAH Assumption
Finance Rate (%)	5%	10%	BAH Assumption

[1]BAH conducted interviews with SAG members in February. Their feedback is documented in SAG document shared with the deliverable package

CAPITAL COST PER PASSENGER MILE

- Capital Cost is the sum of depreciation cost (given by 1) and finance cost (given by 2). Certification costs are included in aircraft price
- **Life time** of the aircraft in years is calculated as the ratio of Vehicle Life (flight hours) and Utilization (hours per year)
- **Residual value** of the aircraft is assumed to be **negligible** since aircraft's value depreciates at rate of ~5-10% in its life time

$$Depreciation\ Cost = Aircraft\ price \times \left(1 - e^{-depreciation\ rate)}\right) ---(1)$$

$$Finance\ Cost = Aircraft\ price \times finance\ rate \times \frac{(1 + monthly\ finance\ rate)^{12 \times Loan\ Term}}{(1 + monthly\ finance\ rate)^{12 \times Loan\ Term - 1}} ---(2)$$

where,

$$monthly\ finance\ rate = \frac{finance\ rate}{12}$$

Aircraft Type	Median Capital Cost per passenger mile	Median Capital Cost per vehicle mile
2 Seat Aircraft	$ 1.87	$ 1.87
3 Seat Aircraft	$ 1.65	$ 2.10
4 Seat Aircraft	$ 1.47	$ 2.80
5 Seat Aircraft	$ 1.38	$ 3.50

Figure 109: Capital Cost per Passenger Mile

Analysis assumed that the operator would be required to have full insurance as typically observed in commercial aviation industry. Calculation of insurance cost of an aircraft is subjective in nature as it depends on 6-12 months of recent aviation history. Therefore, this analysis relies on historical insurance cost of helicopters as a percent of vehicle price. Aircraft insurance is a sum of liability and hull insurance for the base year. Age adjustment will be added for future year projections. Liability insurance covers both public and private liabilities while hull insurance covers both in-motion and not-in-motion cases. Insurance cost does not include infrastructure/facilities insurance (bundled under indirect operating cost).

Helicopter	Insurance as a % of aircraft price	
Robinson R22	2.60%	
Robinson R44_1	2.67%	
Robinson R44_2	2.47%	
Robinson R66	2.30%	MIN
Bell 427	3.28%	
Bell 206L3	2.36%	
Agusta Westland 109 Grand New	2.39%	
Agusta Westland 119 Koala	2.78%	
Airbus H120/Eurocopter EC 120B	3.93%	MAX

Source: Aircraft Cost Calculator (2015), Robinson Helicopter Company (2018)

Aircraft Type	Median Insurance Cost per passenger mile	Median Insurance Cost per vehicle mile
2 Seat Aircraft	$ 0.32	$ 0.32
3 Seat Aircraft	$ 0.26	$ 0.30
4 Seat Aircraft	$ 0.22	$ 0.39
5 Seat Aircraft	$ 0.21	$ 0.47

Liability Insurance

- **Passenger:** Protects passengers riding in the accident aircraft who are injured or killed
- **Public Related:** Protects aircraft owners for damage that their aircraft does to third party property, such as houses, cars, crops, airport facilities and other aircraft struck in a collision

Hull Insurance

- **Not-in-motion:** Provides coverage for the insured aircraft against damage when it is on the ground and not in motion
- **In-motion:** Protects an insured aircraft against damage during all phases of flight and ground operation

Figure 110: Insurance Cost per Passenger Mile

13.3.3 Energy Cost Model

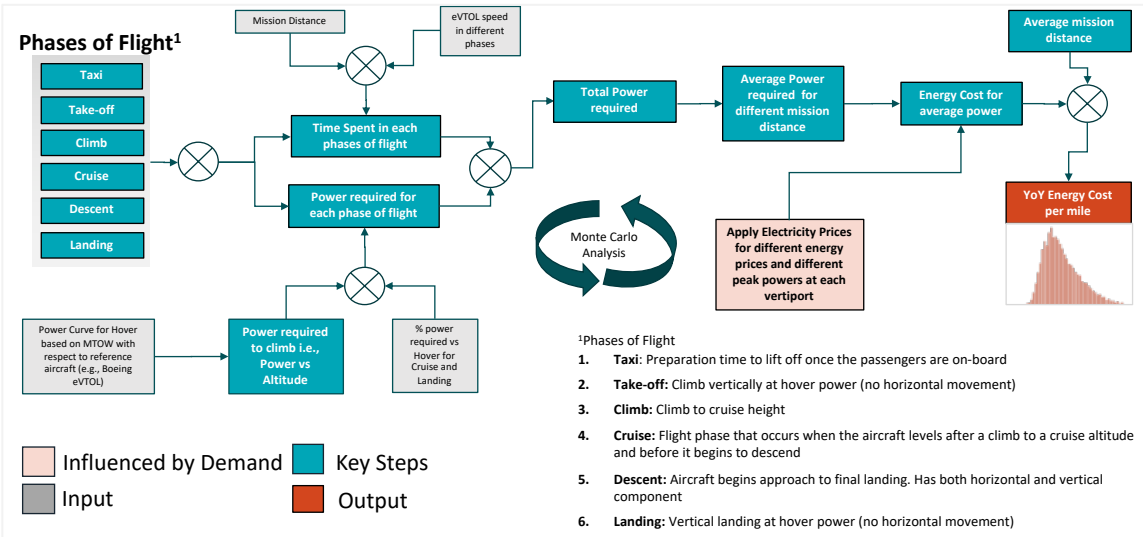


Figure 111: Energy Cost Model

Different aircraft have different battery power requirements. This analysis utilizes research performed by McDonald and German for aircraft with maximum take-off weight of **5000 lb**

s. at mean sea level and standard temperature/pressure conditions. Power requirements specific to different MTOW is calculated in the next slide.

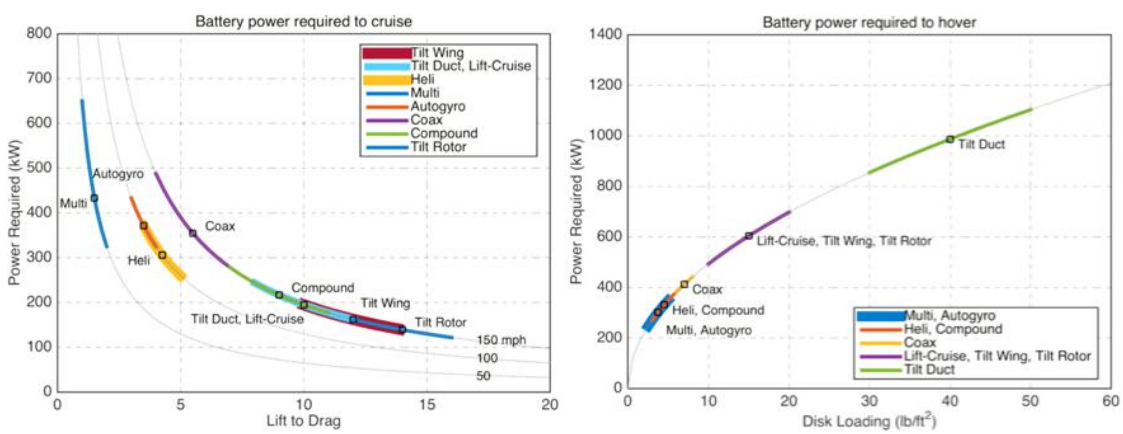


Figure 112: Hover and Cruise power requirement (source: McDonald, R et al.)

ASSUMPTIONS

Parameter	Min	Max	Source
Height of landing and take-off sites (ft)	0	200	BAH Assumption
Climb/Descent Distance (miles)	1	2	MIT Study, BAH Assumption
LTO Height (ft)	100	200	
LTO Time (sec)	10	20	
Embarkation time (mins)	3	5	
Disembarkation time (mins)	2	3	
Transition Time (sec)	15	30	BAH Assumption
Power required in descent (as % of P_{hover})	10%	15%	Boeing Study[1] Uber Elevate[2] Lieshman, 2002[3]
Power required in Taxi (as % of P_{hover})	5%	10%	BAH Assumption
Power required in Climb (% of cruise)	130%	150%	BAH Assumption
Energy Conversion efficiency (%)	90%	98%	Georgia Tech Study[4]
Electricity Price ($/kwh)	0.1	0.3	BAH Assumption

[1]*Fast-Forwarding to a Future of On-Demand Urban Air Transportation, Uber Elevate, October 2017*
[2]*Duffy, M. A Study in Reducing the Cost of Vertical Flight with Electric Propulsion. AHS, 2017*
[3]*Lieshman, G. Aerodynamics of Helicopters, 2002*
[4]*Harish, A. Economics of Advanced Thin-Haul Concepts and Operations. AIAA, 2016*

ENERGY COST PER PASSENGER MILE

- **Power required for larger aircraft** (i.e. more seats) is **higher**, and therefore an increase in cost per vehicle mile.
- Energy cost **per passenger mile** for more than 2-seat aircraft is **similar** since power requirement is directly proportional to MTOW (which is based on number of seats).
- Power requirement is **inversely proportional to square root of ambient air density**. Therefore, lighter air (due to warm temperature conditions or higher altitude) requires more power to complete a mission (hence extra cost).
- Current calculations are **based on standard day at mean sea level**. Effect of weather is explored later in the analysis.

Aircraft Type	Median Energy Cost per passenger mile	Median Energy Cost per vehicle mile
2 Seat Aircraft	$ 0.24	$ 0.24
3 Seat Aircraft	$ 0.24	$ 0.35
4 Seat Aircraft	$ 0.21	$ 0.47
5 Seat Aircraft	$ 0.20	$ 0.59

Figure 113: Energy Cost per Passenger Mile

13.3.4 Battery Cost Model

Our analysis sized the battery pack based on the longest mission assumption for the urban air taxi market. For supply side model only, we assumed a standard day operating condition. However, we integrated effects of wind speed, direction, and temperature conditions later in the analysis. We also assumed that batteries have negligible residual value

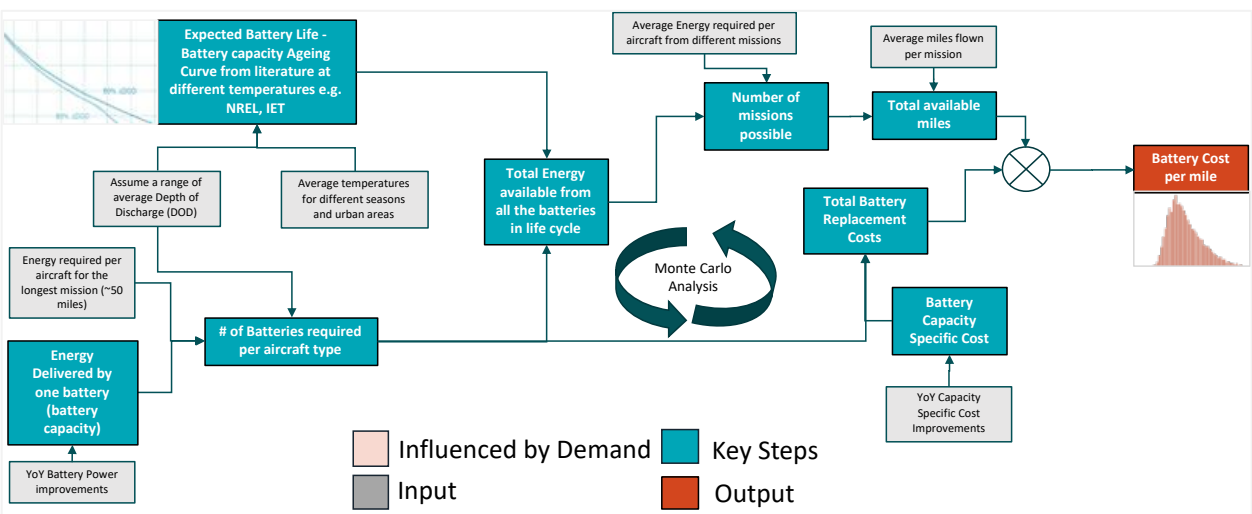
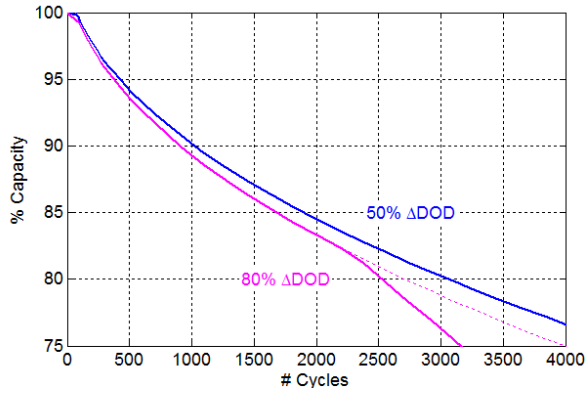


Figure 114: Battery Cost Model

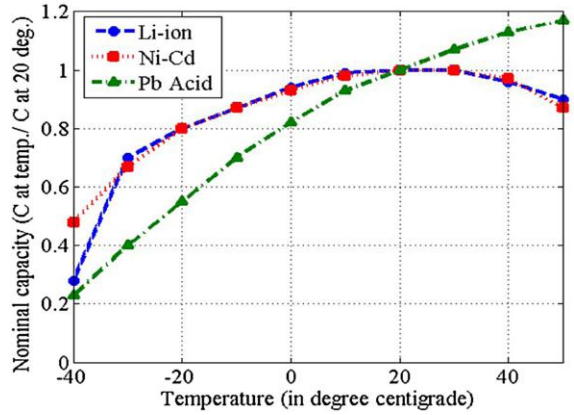
- *Battery life cycle of a Li ion battery directly depends on the depth of discharge (DOD). Increasing DOD decreases battery life. Generalized relationship is shown below:*

$$Life\ Cycle = -1666.7 * Depth_of_Discharge + 3833.3$$



Source: National Renewable Energy Laboratory, 2014

- *Capacity of Li-ion battery decreases at low temperatures since the total resistance (sum of bulk, surface layer and charge-transfer resistance layer) increases*
- *Resistance becomes the most dominant as the temperature goes to below –10°C*



Source: The Institution of Engineering and Technology, 2016

Figure 115: Battery Life Cycle and Capacity Dependencies

ASSUMPTIONS

Parameter	Min	Max	Source
Battery Specific Energy in Wh/kg	300	400	Boeing Study[1]
Battery Capacity Specific Cost ($/kwh)	200	250	Nykvist et al[2]
Depth of Discharge (%)	50%	80%	Georgia Tech Study[3]

[1]*Duffy, M. A Study in Reducing the Cost of Vertical Flight with Electric Propulsion. AHS, 2017*

[2]*Nykvist, B. and Nilsson, M., "Rapidly falling costs of battery packs for electric vehicles," Nature Climate Change, Vol. 5, No. 4, 2015*

[3]*Harish, A. Economics of Advanced Thin-Haul Concepts and Operations. AIAA, 2016*

BATTERY RESERVE COST PER PASSENGER MILE

- Battery[1] cost **increases** as the **size of the vehicle increase** (due to increase in energy requirement). However, battery reserve cost per passenger mile is **similar** for different types of aircraft.
- **Battery specific energy reduces at extreme temperature** conditions, and therefore larger battery size is required which increases the cost.
- Low temperatures have a higher effect on cost in comparison to high temperatures.
- We use Li-ion batteries in this study. Our analysis assumes **negligible battery recycling** since only 3-5% of a lithium battery can be recycled i.e. original amount of lithium by weight in the batteries

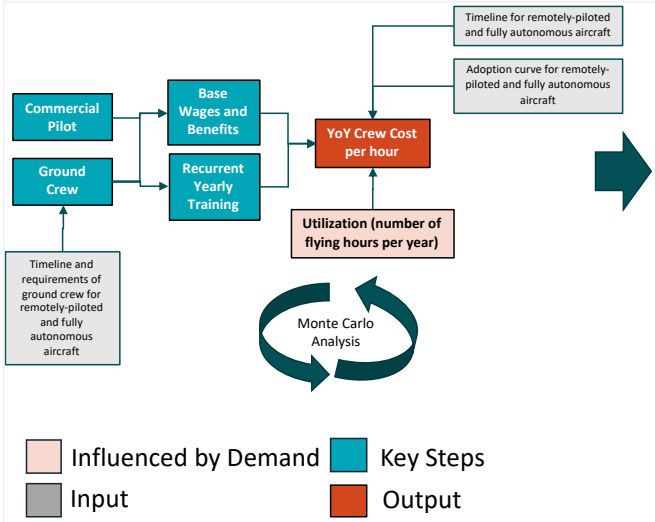
	Median Battery Reserve Cost per passenger mile			Median Battery Reserve Cost per vehicle mile at 20° C
Aircraft Type	20° C	-10° C	50° C	
2 Seat Aircraft	**$ 0.12**	**$ 0.14**	**$ 0.13**	**$ 0.12**
3 Seat Aircraft	**$ 0.17**	**$ 0.19**	**$ 0.18**	**$ 0.23**
4 Seat Aircraft	**$ 0.18**	**$ 0.20**	**$ 0.19**	**$ 0.36**
5 Seat Aircraft	**$ 0.19**	**$ 0.21**	**$ 0.20**	**$ 0.49**

[1]This analysis assumes batteries are recharged by fast chargers as soon as aircraft reach the vertiport with no consideration given to the number of chargers needed or the price of electricity. Various optimization and battery swapping capabilities have been proposed in literature (like Justin et al Georgia Tech), which may reduce the battery requirements.

Figure 116: Battery Reserve Cost per passenger mile

13.3.5 Crew Cost Model

We assumed one full time equivalent pilot per aircraft and one full time equivalent ground crew member in the first few years of the analysis. We assume that the ground crew is expected to serve multiple roles including passenger check-in, security check and any other customer related service.



Monte Carlo Assumptions	Min	Max	Source
Pilot Salary per year (US $)	50, 000	90, 000	Uber Elevate[1], US BLS Helicopter Pilot Salary[2]
Ground Crew Salary per year (US $)	20, 000	30, 000	
Pilot training cost per year (US $)	10, 000	20, 000	
Ground Crew training cost per year (US $)	5, 000	10, 000	

Aircraft Type	Median Crew Cost per passenger mile	Median Crew Cost per vehicle mile
2 Seat Aircraft	$ 2.03	$ 2.03
3 Seat Aircraft	$ 1.13	$ 1.50
4 Seat Aircraft	$ 0.75	$ 1.50
5 Seat Aircraft	$ 0.56	$ 1.50

[1]Uber Elevate white paper available at https://www.uber.com/elevate.pdf
[2]US Department Bureau of Labor Statistics, https://www.bls.gov/

Figure 117: Crew Cost per passenger mile

13.3.6 Infrastructure Cost Model

Our first order infrastructure model assumes car parking garage style architecture and construction with a certain number of parking sites. Our assumption is based on the market's interest to use a multi-purpose garage (like top of garage roof) for operating air taxis in the near term. However, there are number of terminal type designs proposed by OEMs, which are expected to have higher cost.

Step 1: We retrieve cost of constructing a parking space from literature, adjusted by area required for aircraft size. Depending on the number of chargers and parking sites, total cost of building is calculated (financed over a certain amortization period).

Step 2: Each parking garage is expected to have yearly parking income from overnight parking of Air Taxis.

Step 3: The net cash required (yearly cost of building – yearly parking income) is divided by utilization and number of operations per hour to calculate landing fees per hour (which is further divided by trip speed to calculate landing fees per mile)

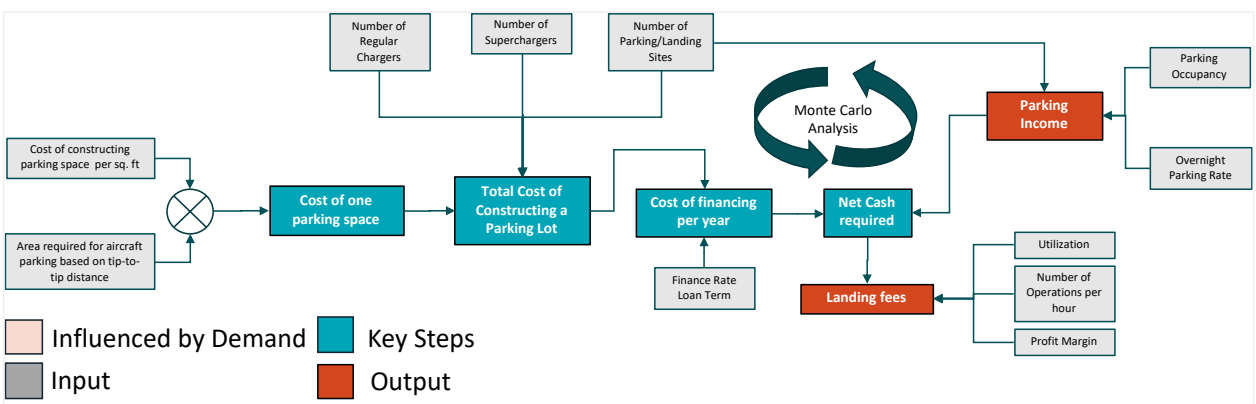


Figure 118: Infrastructure Cost Model

ASSUMPTIONS

Parameter	Min	Max	Source
Tip-to-Tip length of aircraft (m)	5	15	BAH Assumption
Number of Parking/Landing Spots	1	12	BAH Assumption
Number of Superchargers (% of landing spots)	0%	30%	BAH Assumption
Number of regular chargers (% of landing spots)	0%	50%	BAH Assumption
Cost of one supercharger (US $)	200, 000	300, 000	Uber Elevate[1]
Cost of regular charger (US $)	10, 000	15, 000	Uber Elevate
Indirect Costs (% of total cost)	15%	25%	BAH Assumption
Overnight parking costs (US $)	50	75	BAH Assumption
Parking Occupancy Rate (%)	50%	100%	BAH Assumption

[1] *Fast-Forwarding to a Future of On-Demand Urban Air Transportation, Uber Elevate, October 2017*

INFRASTRUCTURE COST PER PASSENGER MILE

- On average, the **cost to build one parking spot** (in a car parking garage style) will cost approximately **~ $15,000** without including any type of charger. This cost varies by real estate prices of an urban area. Our analysis assumes an average of ~$60/ft^2 across urban area.
- In comparison, **other studies have reported higher infrastructure cost per passenger mile** (e.g. Uber Elevate reported over $1.5 per passenger mile during the 2018 Uber Elevate Summit). Higher cost is likely due to the power line installation costs and terminal design of the infrastructure that includes extra amenities like lounge areas, shopping, cafés etc.

Aircraft Type	Median infrastructure Cost per passenger mile	Median infrastructure Cost per vehicle mile
2 Seat Aircraft	$ 0.53	$ 0.53
3 Seat Aircraft	$ 0.38	$ 0.53
4 Seat Aircraft	$ 0.25	$ 0.53
5 Seat Aircraft	$ 0.19	$ 0.53

- Infrastructure designs may be influenced by community noise signatures, public acceptance, capacity requirements (influenced by demand), airspace constraints, routing, power grid capacity etc.

Figure 119: Infrastructure cost per passenger mile

13.3.7 Maintenance Cost Model

ASSUMPTIONS

Parameter	Min	Max	Source
Mechanic Wrap Rate ($ per hour)	$60	$100	MIT Study[1]
Maintenance man-hours per flight hour (MMH/FH)	0.25	1	
Mechanic Wrap Rate ($ per hour)	$60	$100	

[1] *Brown, A. A Vehicle Design and Optimization Model for On-Demand Aviation, 2018*

MAINTENANCE COST MODEL

- Maintenance cost per mission is calculated using the following equation

$$Maintenance\ Cost = Mechanic\ Wrap\ Rate \times \frac{MMH}{FH} \times t_{mission}$$

where,

Mechanic Wrap rate is the hourly rate of mechanic

MMH/FH : Ratio of maintenance man hours to flight hours

$t_{mission}$ is the average mission time for range of mission distances (including time spent on the ground)

- Our analysis assumes **similar maintenance cost** for different size of aircraft (usually, maintenance cost is higher for larger aircraft)

Aircraft Type	Median Maintenance Cost per passenger mile	Median Maintenance Cost per vehicle mile
2 Seat Aircraft	$ 1.88	$ 1.88
3 Seat Aircraft	$ 1.45	$ 1.88
4 Seat Aircraft	$ 0.97	$ 1.88
5 Seat Aircraft	$ 0.72	$ 1.88

Figure 120: Infrastructure cost per passenger mile

13.3.8 Route Cost Model

Route cost in commercial aviation refers to **fees paid to air traffic control** while crossing their managed airspace. In urban air mobility, these fees may be collected at administrative zone level. The route charge is usually calculated using three basic elements:

- **Distance factor** (for each charging zone) i.e., distance flown in a particular zone
- **Aircraft weight**
- **Unit rate of charge** (for each charging zone)

For this analysis, we obtained historical route cost per seat per mile for commercial business jets flown in United States to develop the minimum and maximum range as shown in table below.

Business jet Type	Route cost per seat per mile	
Very Light Business Jet	0.0079	MIN
Light Business Jet	0.0081	
Corporate Business Jet	0.0162	MAX

Source: Bureau of Transportation Statistics, 2018 ; OAG, 2018

Aircraft Type	Median Route Cost per passenger mile	Median Route Cost per vehicle mile
2 Seat Aircraft	**$ 0.04**	**$ 0.04**
3 Seat Aircraft	**$ 0.05**	**$ 0.06**
4 Seat Aircraft	**$ 0.04**	**$ 0.08**
5 Seat Aircraft	**$ 0.04**	**$ 0.10**

Figure 121: Route Cost per passenger mile

13.3.9 Indirect Operating Cost Model

Commercial aviation industry reports approximately 10-30% in indirect costs associated with operations. (Source: ICAO, Form 41, Boeing Forecasts, MIT Airline Project). Since operations of urban Air Taxis and Airport Shuttles are expected to be similar to commercial aviation, our analysis adopts similar percentages for indirect cost calculations. Part of these costs (like reservation, ticketing cost etc.) may be irrelevant for UATs.

NON-EXHAUSTIVE

Indirect Cost Component	Min	Max	Passenger price per mile / Per vehicle mile			
			2 Seat Aircraft	3 Seat Aircraft	4 Seat Aircraft	5 Seat Aircraft
1. **Reservation Cost** – Need to arrange booking and connect passengers with vehicles 2. **Ticketing Costs** – Administrative costs to ensure that passengers can fly 3. **Credit Card Processing Fees** – Recently upheld by the Supreme Court, credit card companies charge merchants for using their cards 4. **Marketing –** "If you don't keep giving customers reasons to buy from you, they won't." – Sergio Zyman, former head of marketing at Coca Cola 5. **Building –** Need a place for vehicles to land and take off 6. **Hangar –** Need a place to store and repair/maintain vehicles	10%	30%	$1.74 / $1.74	$1.29 / $1.40	$1.02 / $1.68	$0.88 / $2.00

Figure 122: Indirect Operating Cost per passenger mile

13.3.10 Taxes and Fees

Urban Air taxis may be charged similar taxes and fees like on demand taxis or ride sharing services. The list below shows possible tax codes (not exhaustive) that may be levied on UATs.

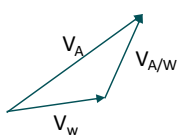
			Passenger price per mile / Per vehicle mile			
Type of Tax	Min	Max	2 Seat Aircraft	3 Seat Aircraft	4 Seat Aircraft	5 Seat Aircraft
1. **Sales tax** – Charged by state at the point of purchase 2. **Commercial Motor Tax** – Charged by municipalities on vehicles for business use 3. **Workers Compensation Fund** – May be for pilots' union or manufacturers 4. **Surcharge for Public Transportation** – Municipalities are beginning to charge rideshare taxes to pay for public transit (Following Chicago's example, DC is trying to increase tax from 1% from 4.5%) 5. **Surcharge for Accessibility** – Introduced in New York, charges all riders to provide funds to make vehicles accessible to the disabled 6. **Licensing Fees** – For technology (i.e. batteries or engines) or trademarks (i.e. brand names) 7. **Recall Charges** – As needed in case of flawed equipment 8. **Inspection Fees -** Needed to pay for certification 9. **Environment Tax -** Depends on location, may include carbon offset fees 10. **Local/State property tax –** Depends on location, may be charged to vertiport owners	5%	15%	$1.24 / $1.24	$0.93 / $1.16	$0.73 / $1.32	$0.63 / $1.58

Figure 123: Taxes and Fees per passenger mile

13.3.11 Weather Adjustments

True Airspeed

- To determine the true airspeed of eVTOL (A) with respect to wind direction (w) at a **certain altitude**, the time derivative of the relative position equation is taken i.e.



$$\boldsymbol{V_{A/w} = V_A + V_w}$$

where,

V_A is aircraft velocity in the direction of motion (i.e. mission direction)

V_W is wind speed at different altitudes for a particular urban area

$V_{A/W}$ is the relative velocity. Our analysis adjusts the eVTOL speed to the magnitude of relative velocity at a certain altitude

Temperature

- **Battery specific energy reduces at extreme temperature conditions**, and therefore larger battery size is required which increases the cost
- Since temperature changes with altitude, battery sizing is done **by integral (or summation) of battery requirements at different phases of flight** for the longest mission

$$Battery\ requirement = \int_{h=h_t}^{h=h_l} dB_t$$

where,

h_t refers to take-off sight altitude

h_l : landing sight altitude

dB_t : Battery requirement for each phase at different altitude (100 ft interval) i.e. different temperature

Ambient Density

- **Performance** of an eVTOL varies with air **density**. Higher density means less power while lighter air (lower density) requires more power to lift and take-off.
- Air density **varies with temperature and altitude** as shown in the formula below

$$\frac{\rho}{\rho_0} = \int_{h=h_t}^{h=h_l} \frac{288.16}{T + 273.16} \times \left(1 - \frac{h}{k}\right)^{5.256}$$

where,

h refers to flying altitude (msl)

T: Temperature in °C

k : constant (2.255×10^{-5})

ρ_0: 1.225kg/m^3 (air density at standard temperature pressure)

Source: Lieshman, G. Aerodynamics of Helicopters, 2002

*Weather adjustment is done specific to an urban area and applied during demand analysis

Figure 124: Weather Adjustments in a mission

13.3.12 Trip Production and Attraction

Airport Shuttle

- We first set up our model based using Bureau of Transportation Statistics, T-100 Market (All Carriers) data to focus on passengers traveling to and from US airports after scoping as shown in previous slide
- Scoped daily demand from each airport in an urban area is distributed proportionally to the population of census tract.

Trip Production (Origin, O)	**BTS T-100 Market (All Carriers)** **Scope**: Passenger traveling to and from US airports after scoping as shown in previous slide
Trip Attraction (Destination, D)	**ACS Table B01003** *Total Population* **Scope**: All members of household greater than 2 years of age

Source: American Community Survey (ACS) , 2016 (5 year estimates)

Air Taxi

US Department of Transportation provides guidance on value of travel time savings (VTTS) for passengers on mandatory (i.e., work related) and discretional (i.e. personal) trips.

- In general, **VTTS is estimated to be half for personal travel** when compared to work related travels i.e. a passenger on a personal trip would be willing to pay half as compared to work trip for same amount of travel time savings
- We first set up our model based on **mandatory work related trips** to calculate work-related demand. Our next iteration of analysis would apply similar trip distribution for discretional trips to calculate final demand

Trip Production (Origin, O)	**ACS Table B08134** *Means Of Transportation To Work By Travel Time To Work* **Scope**: Workers 16 years and over who did not work at home (tract Level)
Trip Attraction (Destination, D)	**ACS Table B99081** *Imputation of Place of work* **Scope:** Workers 16 years and over who did not work at home (tract Level)

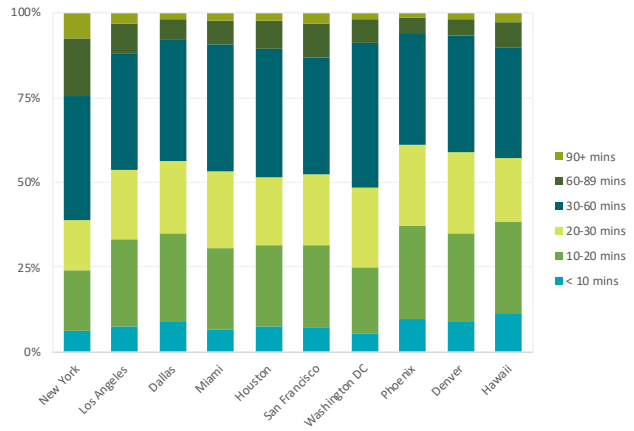
Source: American Community Survey (ACS) , 2016 (5 year estimates)

Figure 125: Trip Production and Attraction process

13.3.13 Trip Share by Travel Time and Mode

Trip Share by Travel Time

25% work trips in the New York *urban area require more than 60 mins total travel time on a daily basis. These trips can be potentially served by UAM.*



Trip Share by Mode Type

Driving is the most preferred choice for work *related trips in most urban areas except New York and Washington D.C. (both have good public transportation systems).*

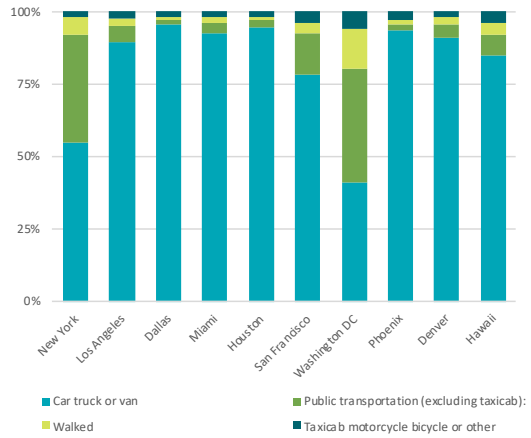
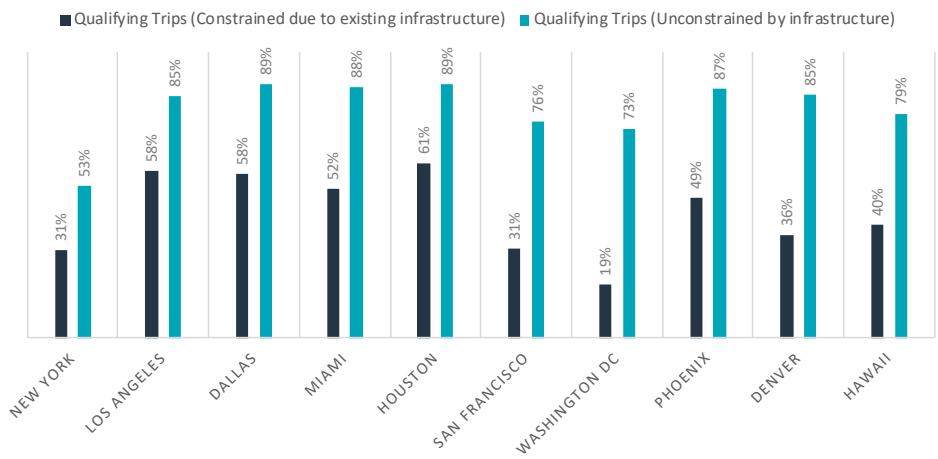


Figure 126: Trip Share by Travel Time and Mode (source: ACS, 2016)

13.3.14 Qualifying UAM trips

Utility of Urban Air Mobility is to reduce travel time as compared to major competing modes of transportation (like driving, ride-sharing, public transportation etc.). Therefore, this analysis applies a rule where UAM total travel time (on ground time and air time) is less than travel time for ground transportation to calculate total available market. Cases of Los Angeles, Miami, Houston, Dallas, and Phoenix shows that the existing infrastructure captures large part of the available market.



Urban Area	Total Daily Work Trips (mn)
Dallas	2.7
Denver	1.2
Hawaii	0.6
Houston	2.4
Los Angeles	5.9
Miami	2.4
New York	8.2
Phoenix	1.6
San Francisco	2.4
Washington DC	2.3

Source: American Community Survey, 2016

Figure 127: Qualifying Trips

13.3.15 Multinomial Logit Model

We choose Probabilistic Choice models over Deterministic utility models since it is difficult to understand the decision process of each individual or their perceptions while choosing a certain mode. Multinomial Logit Model allows us to describe preferences and choice of a user in terms of probabilities of choosing each alternative rather than predicting that an individual will choose a particular mode with certainty. The general expression for the probability of choosing an alternative 'i' (i = 1,2,.., J) from a set of J alternatives is

$$\Pr(i) = \frac{\exp(Vi)}{\sum_{i=1}^{j} \exp(Vi)}$$

where,

Pr(i) is the probability of the decision-maker choosing alternative i

V_i is the systematic component of the utility of alternative i. Alternatives includes all forms of transportation system

13.3.16 Willingness to Pay Constraint

US Department of Transportation provides guidance on valuation of travel time in economic analysis. For business travelers doing local travel, VTTS is assumed to be 80%-120% per person hour as a percentage of total earnings. The figure below shows change in VTTS as a function of median household income. Willingness-to-pay for UAM is calculated as a function of travel-time savings when compared to ground transport and can be generalized using the formula below:

$$WTP_uam = Cost_m + (Tm - T_{UAM}) * VTTS$$

where,

$Cost_m$ = Cost of using an alternative mode, m for a mission

Tm = Time required by mode m to complete a mission

T_{uam} = Time required using UAM to complete a mission

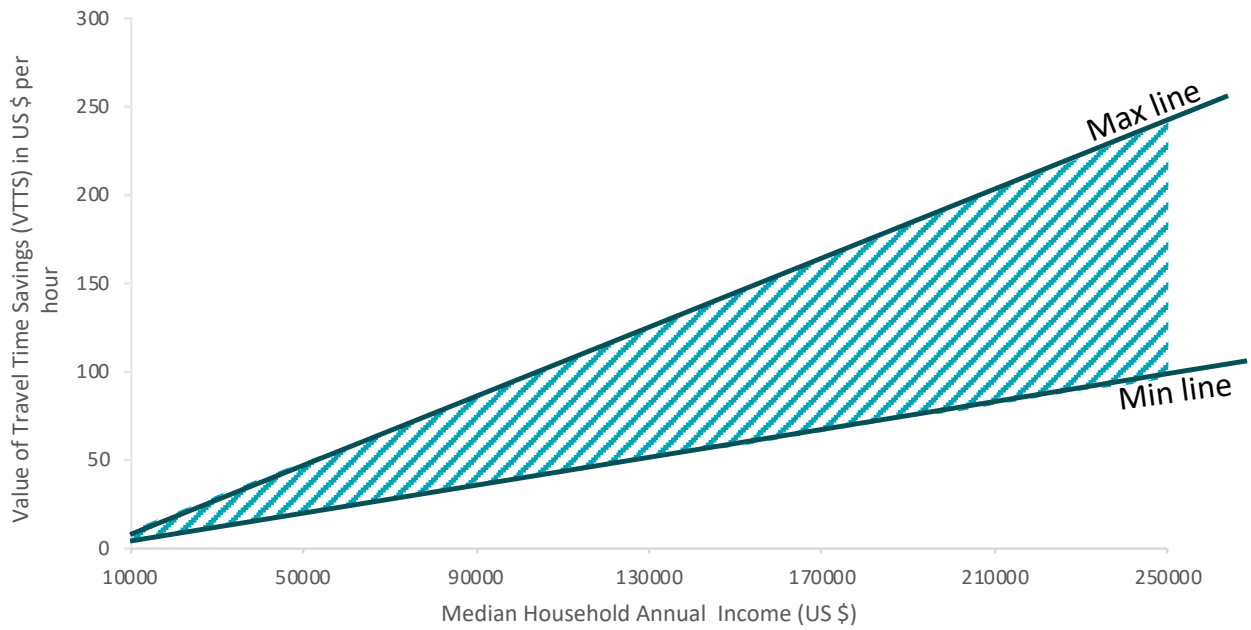


Figure 128: VTTS uncertainty line

13.3.17 Infrastructure Capacity Constraint

ASSUMPTIONS

Parameter	Min	Max	Source
Embarkation Time (mins)	3	5	MIT Study[1]
Disembarkation Time (mins)	2	3	
Airspace Clearance (sec)	30	60	
Delay at Vertiport (mins)	1	10	BAH Assumption

[1]*Vascik, P. Systems-level Analysis Of On Demand Mobility For Aviation. MIT, 2017*

INFRASTRUCTURE CAPACITY CONSTRAINTS

- Heliports/Vertiport operational capacity in the form of flights per hour depends upon **aircraft total turn-time** during loading (**embarkation**) and unloading (**disembarkation**), time required for the departing aircraft to lift off and **clear the airspace** in proximity, and **delay** caused by the security time and late arrival of the taxi (may be due to hovering or delay in arrival from its parked/charging location).
- Aircraft **on-pad turn time** is defined as sum of embarkation and disembarkation time

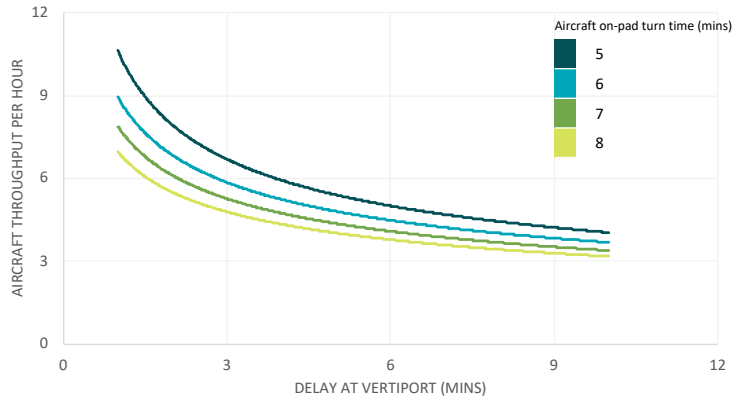
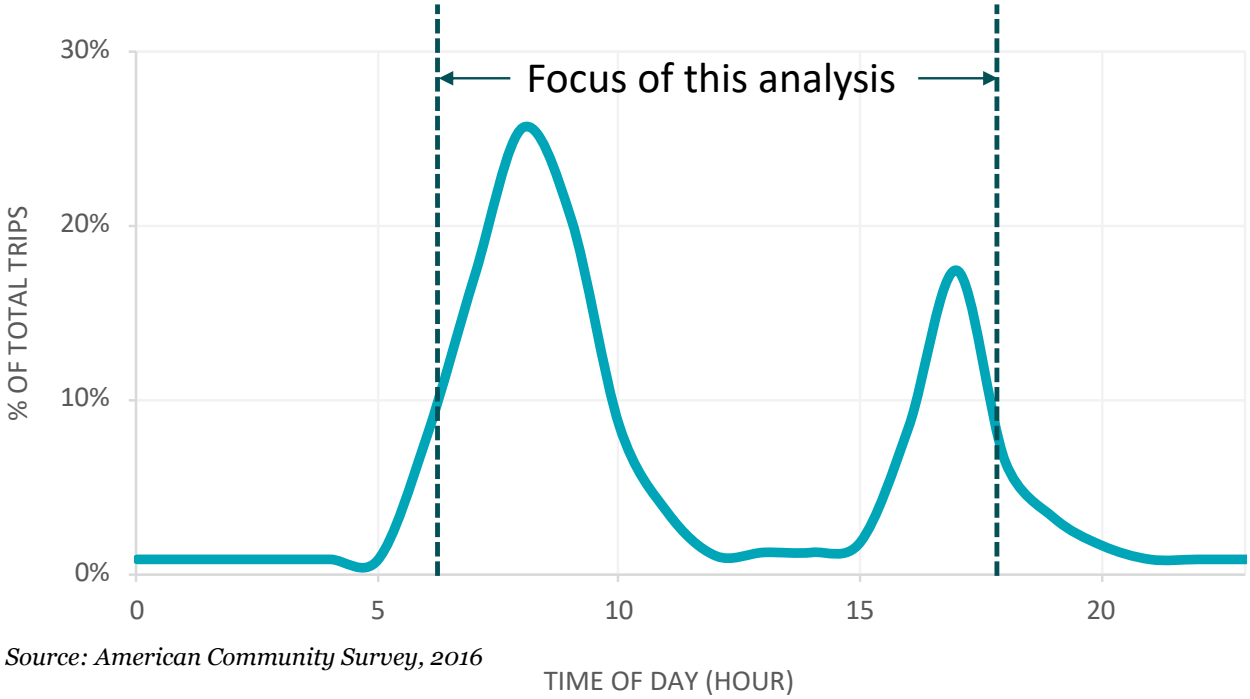


Figure 129: Infrastructure Capacity Constraint

13.3.18 Time of Day Restrictions

Heliports/Vertiports and UAM service providers are expected to operate for specific time of day that is determined by various factors like demand, legal/regulatory restrictions, weather, etc. Demand in usually high between 7-10 am and 3-6 pm as evident from the graph below. Therefore, for the purpose of this analysis we assume heliports/vertiports operating schedule to be 7 am to 6 pm.



Source: American Community Survey, 2016

Figure 130: Time of Day Restrictions

13.3.19 Weather Constraints

Near term operations in the US are expected to be under Visual Flight Rules (VFR) conditions. IFR conditions are usually prevalent in the morning rush hour as evident from the graph below. Urban Areas like San Francisco have low VFR conditions between 7 am-11 am that can limit the number of operations and reduce the reliability of Air Taxi operations.

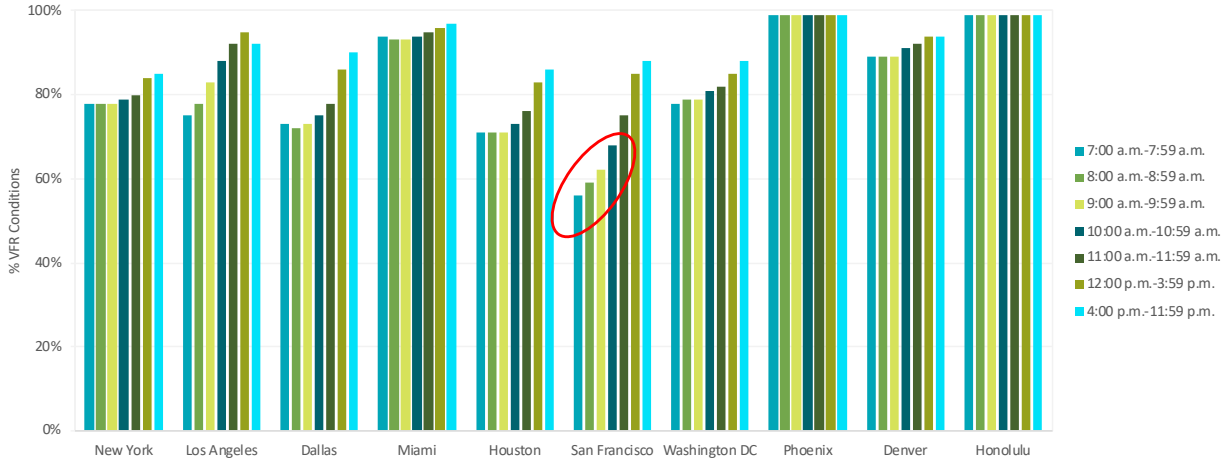
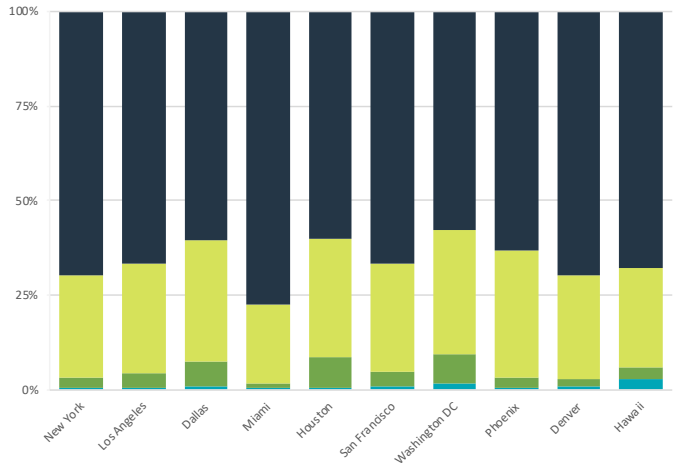


Figure 131: VFR conditions at each urban area

13.3.20 Market Share by Aircraft type



	Number of Aircraft Required				
	2-Seat	3-Seat	4-Seat	5-Seat	Total
New York	2	11	113	294	420
Los Angeles	1	14	103	236	354
Dallas	2	16	77	145	240
Miami	1	2	29	109	141
Houston	2	17	68	130	217
San Francisco	1	3	19	43	66
Washington DC	1	3	12	22	38
Phoenix	1	3	34	65	103
Denver	1	1	17	42	61
Hawaii	1	1	6	15	23
Total	13	71	478	1101	**1663**

[1] Market share of a UAM aircraft will also depends upon availability of each type of aircraft (i.e., delivery year), environmental impact, flexibility, user preference, size, infrastructure requirements etc. This analysis calculates market share based on operating cost of an aircraft

Figure 132: Market Share by Aircraft type for each Urban Area