Escola d'Enginyeria de Telecomunicació i Aeroespacial de Castelldefels

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FINAL DEGREE THESIS

TITLE: Assessing the airport facilities in the context of UAM operations

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AUTHOR: Álvaro Hernando López

DIRECTOR: Jovana Kuljanin

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Resumen

La movilidad de la UAM se considera como un cambio de paradigma en el modo de transporte de pasajeros para el transporte intra e interurbano. Este concepto está respaldado por la aparición de nuevos tipos de aviones con la capacidad de despegue y aterrizaje vertical (VTOL) y el uso de propulsión eléctrica y almacenamiento de energía. Los prototipos actuales de vehículos VTOL varían sustancialmente en configuración y diseño, lo que deriva en diferentes misiones y conceptos de operaciones de la UAM. Aunque todavía se encuentran en una fase de prototipado, el creciente interés por parte de grandes inversores y empresas existentes (NASA) y emergentes (Lilium) hace que se espere que algunos de estos aviones VTOL acaben siendo autónomos y sin piloto diseñados para entre uno y cinco pasajeros a bordo.

Si bien la mayor parte del servicio relacionado con los pasajeros de la UAM requerirá una infraestructura terrestre VTOL dedicada para el despegue y el aterrizaje (a menudo denominados vertipuertos), algunos de los conceptos operativos contemplan la integración de estos vehículos en los aeropuertos existentes. Esto se refiere particularmente a la misión de la UAM que tiene como objetivo conectar el centro de la ciudad (o suburbio) con el aeropuerto. Sin embargo, este proceso no es sencillo, ya que requiere una evaluación exhaustiva de diferentes aspectos operativos y de seguridad para permitir la operación sin problemas de estos nuevos vehículos dadas sus características distintivas. Además, para dar cabida a este tipo de vehículos y brindar un nivel de servicio satisfactorio a todas las partes interesadas (es decir, las aerolíneas), los aeropuertos deberán adquirir instalaciones adecuadas y aprender a gestionar estas nuevas operaciones junto con la aviación convencional.

Este proyecto tiene como objetivo investigar la necesidad de nuevas instalaciones aeroportuarias a la luz de la posible integración de vehículos VTOL. Con sus nuevas características de autonomía, algunas de las facilidades de la zona de operaciones deben actualizarse radicalmente para permitir la integración segura en el sistema aeroportuario actual. Para ello, este análisis se divide en dos partes. La primera parte está orientada a la descripción y el análisis de los distintos modelos y configuraciones de aeronaves VTOL que pueden encontrarse en la actualidad y a la naturaleza de las misiones que pueden desenvolver. La segunda parte del estudio introduce un trasfondo y un enfoque inicial a la integración de los servicios UAM en el entorno aeroportuario para terminar analizando dos hipotéticos escenarios de aplicación a la realidad con su correspondiente identificación de las nuevas y existentes facilidades necesarias para acomodar a estos nuevos conceptos de operaciones.

Overview

UAM mobility is deemed as a paradigm shift in passenger transport mode for intra- and inter-urban transport. This concept is supported by the appearance of new types of aircraft with the capability of vertical takeoff and landing (VTOL) and the use of electric propulsion and energy storage. Current VTOL vehicle prototypes vary substantially in configuration and design, resulting in different UAM missions and concepts of operations. Although still in the so-called innovation trigger phase, growing interest from large investors and existing (NASA) and emerging (Lilium) companies implies the expectation of some of these VTOL aircraft to end up being pilotless, autonomous aircraft designed for between one and five passengers on board.

While most of the UAM passenger-related service will require dedicated VTOL ground infrastructure for takeoff and landing (often referred as vertiports), some of the operational concepts contemplate integrating these vehicles into existing airports. This refers particularly to the UAM mission which aims to connect the city center (or suburb) with the airport. However, this process is not straightforward, as it requires a thorough evaluation of different operational and safety aspects to allow the smooth operation of these new vehicles given their distinctive characteristics. Furthermore, to accommodate these types of vehicles and provide a satisfactory level of service to all stakeholders (i.e., airlines), airports will need to acquire adequate facilities and learn to manage these new operations alongside conventional aviation.

This project aims to investigate the need for new airport facilities in the light of potential integration of VTOL vehicles. With their new autonomy features, some of the airside facilities need to be radically upgraded to allow safe integration into the current airport system. To do this, this analysis is divided into two parts. The first part is oriented to the description and analysis of the different models and configurations of VTOL aircraft that can be found nowadays together with the nature of the missions that can be carried out. The second part of the study introduces a background and an initial approach to the integration of UAM services in the airport environment to finish by analysing two hypothetical application scenarios to reality with their corresponding identification of the new and existing facilities necessary to accommodate these new operations concepts.

Acknowledgements

First of all, I would like to thank my mentor and tutor throughout this project, Dr. Jovana Kuljanin. For her dedication and for having guided and helped me at all times pushing me forward when I needed it most. Thank you also for understanding how busy I have been these last months and for always being willing to give me new ideas to correct and improve this project.

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Last but not least, I would like to thank myself for the effort I have invested over the last few years and for never giving up. Combining college with internship, sports, and a few other hardships encountered along the way has not been easy, but I have always managed to keep going. Now for new challenges!

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Abbreviations

ADS-B: Automatic Dependent Surveillance-Broadcast

AGL: Above Ground Level

ATC: Air Traffic Control

CDF: Cumulative Distribution Function

CFR: Code of Federal Regulations

CNS: Communication, Navigation and Surveillance

ConOps: Concept of Operations

DEP: Distributed Electric Propulsion

EASA: European Aviation Safety Agency

EoR: Established on RNP

FAA: Federal Aviation Administration

FAR: Federal Aviation Regulations

FATO: Final Approach and Take-Off)

GA: General Aviation

ICAO: International Civil Aviation Organization

IFR: Instrumental Flight Rules

LAHSO: Land And Hold Short Operations

MAPt: Missed Approach Point

METAR: Meteorological Terminal Aviation Routine

MSL: Mean Sea Level

MTOM: Maximum TakeOff Mass

NASA: National Aeronautics and Space Administration

OEW: Operating Empty Weight

PBN: Performance-Based Navigation

PinS: Point in Space

RNP: Required Navigation Performance

RVLT: Revolutionary Vertical Lift Technology project

SCIA: Simultaneous Converging Instrument Approaches

STOL: Short TakeOff and Landing

TCAS: Traffic and Collision Avoidance System

TLOF: Touchdown and Lift-OFF

TOLA: TakeOff and Landing Area

UAM: Urban Air Mobility

VFR: Visual Flight Rules

VFS: Vertical Flight Society

VTOL: Vertical TakeOff Landing

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1. INTRODUCTION

UAM is a topic that has recently been arousing the interest of both industry and research in the aeronautical world and aviation. However, this is not a new concept, since the idea of using flying vehicles within urban areas dates back to the 1940s with the invention of helicopters, vehicles that, as we know, have the ability to vertically take-off and land (VTOL).

For example, between 1947 and 1971, an airline, Los Angeles Airways, used helicopters to transport people and mail within the Los Angeles metropolitan area, including shuttle services between Disneyland and Los Angeles International Airport (LAX) [1]. However, several accidents, due in large part to low technological maturity coupled with the production of high noise levels and high operational costs, forced many of the helicopter operators in the US and Europe to cease their operations in the late 1960s.

Currently, helicopter-based passenger transport exists within charter operations or even on-demand air services for various large cities (for example, the helicopter option appears in the Uber app to offer transfers from Manhattan to JFK International Airport in just eight minutes [2]). These current services mark an important starting point for the introduction of UAM, as they provide researchers and large companies with information on consumer preferences (popular routes, willingness to pay) and the operational challenges related to public acceptance, lack of infrastructure or air traffic congestion.

In addition, new advances in technology and mobility have allowed the appearance and development of new improved concepts of VTOL vehicles, powered by increasingly efficient fully electric motors that will be able to reduce operating costs, thus stimulating the implementation and demand of the UAM. Various stakeholders ranging from the main aeronautical entities and companies (NASA, Airbus, Boeing, etc.) to new start-ups and emerging companies dedicated solely to the study of these aircraft (Lilium, Volocopter, NEVA Aerospace, etc.) have various projects and studies underway on this type of concepts from which, as will be seen later, various models and configurations arise depending on their design and their operational characteristics.

Today, VTOL vehicles are still in a prototyping phase, however, many of these models have successfully completed their first tests and pilot flights, so it is to be expected that in the near future we will begin to see this type of aircraft flying over the skies of our cities. Ultimately, the UAM concept aims to revolutionize mobility around urban areas by providing a safe, efficient and accessible on-demand air transportation system for passengers and cargo, thus managing to reduce the increasing traffic congestion in large cities.

In addition to passenger transport, the UAM is intended to cover a wide variety of operational concepts such as medical emergency missions, logistics, surveillance and other. However, in this study the author will focus on contemplating its possible operations within an airport environment. That is why, based on the current helicopters and small aircraft that operate in the general aviation framework, the main objective of this thesis is to identify and analyze the new and existing facilities necessary to accommodate these new VTOL vehicles in the current airport system with the aim of ensuring that both established conventional operations and new UAM operations can be carried out in accordance in a safe and efficient manner.

It is important to appreciate that the UAM industry is still in its early stages of development and that, therefore, due to a lack of specific and detailed information on the characteristics and performance of these vehicles, it is not possible to propose a specific solution and ensure its applicability. Some assumptions have to be made in order to be able to draw valid conclusions so then, this study has a rather theoretical approach, based, as mentioned, on helicopter and general aviation operations as the main referents. Furthermore, hypotheses may change as new studies are presented and it should be understood that this project presents its conclusions and findings based on the limited technical information available at the time of writing.

2. Methodological framework

In order to achieve the objective of this thesis by proposing a solution that is as solid as possible given the current circumstances, this document is divided into sections. In each of them, the author will address a series of objectives that will allow him to reach the final conclusions. The thesis adopted the descriptive approach based on the rigorous engineering principles, mainly due to the fact that the UAM concept is still very vague and subject to large number of speculations and assumptions. It entails that some information which is essential for UAM operations are still not publicly available. However, the author endeavored to base his assumptions and hypothesis regarding the required infrastructure to support UAM operations on the relevant and available academic literature as well as industrial reports.

To begin with, section 3 is devoted to the identification and analysis of the various VTOL vehicle designs and configurations found in the current literature. This will allow us to get an idea of what each type of vehicle can give and understand that, depending on its design and performance, there will be missions that are better suited to some vehicles or others.

Next, section 4 is oriented to define the main missions and their operational nature for which this type of aircraft are mainly designed. Here, a general mission profile will be introduced, with its different flight stages (taxi, transition, climb, etc.) similar in part to that followed by commercial aviation, and three types of missions proposed by NASA will be analyzed as they are intended to be the main potential markets for UAM in terms of viability and operational efficiency [3].

Section 5 begins by investigating the operations that are currently carried out in the airport environment in an unconventional or charter manner, that is, general aviation and helicopter operations. Then, five operational schemes found in the literature will be introduced, describing five different approaches for the implementation of UAM in airports depending on the distance at which these operations are carried out with respect to conventional operations. This marks an important starting point for the integration of the UAM, since the author will be able to project a tangible solution based on operations already implemented and on hypothetical scenarios that mark different operational limitations depending on the UAM operations nature.

Section 6 develops the main findings found by the author. It begins with a contextualization of the main objective, analyzing a theoretical model of vertiport and taking as reference two aircraft belonging to the two groups in which VTOL vehicles are classified in a more general way, the Lilium JET belonging to the family of Fixed -Wing aircraft and the VoloCity of the Rotary-Wing aircraft group. After analyzing each of these models characteristics, the first conclusions of the section are presented: depending on the design and performance, some aircraft will tend to use the existing infrastructure at airports due to their similarity to conventional aircraft, while for others it will be indisputable the creation of new facilities and vertiports necessary for its correct integration. After this first finding, two scenarios will be presented: a scenario in which some vehicles use the existing facilities in the airport environment for their operation and another scenario in which it will be necessary to implement new infrastructure to accommodate the other type of models. Each of these scenarios will be presented specifying some operational aspects and finally, a table will be drawn up for each of them, identifying and analyzing the main airport services necessary to accommodate each of the configurations.

Finally, the thesis closes with a series of personal assessments and conclusions about the findings found and the research carried out.

Figure 2.1 below shows graphically in a flow chart the methodology followed in the elaboration of this thesis:

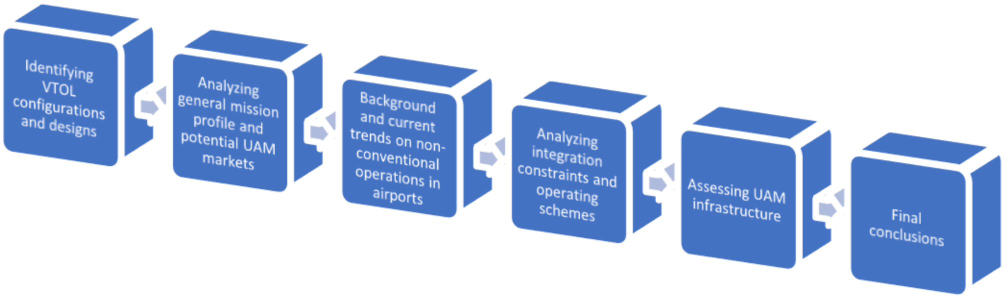


Figure 2.1. Thesis methodology flow chart [own elaboration].

3. VTOL designs and configurations

The design of VTOL vehicles is a fundamental element for the successful implementation of UAM operations in the airport and inter-urban environment since it allows us to know the specific characteristics of these vehicles and the nature of the operations they will carry out.

This aspect, in turn, promises to be a great lucrative opportunity for potential manufacturers and the aviation industry in general, since, once the test phase is over, several market forecasts predict high production volumes. That is that only in the research and design of these vehicles, more than 2 billion dollars have already been invested [4]. A market study commissioned by NASA predicts a short-term demand of about 55,000 daily trips within the airport environment and shuttles to airports from various U.S. urban centers under restrictions due to external factors such as weather, restrictions by the available space, willingness to pay of potential customers, etc. From then on, with less restricted scenarios, daily travel demand in this environment is expected to increase to eleven million within the U.S. [5]. Therefore, taking into account the number of units sold to cover this demand, the market for VTOL vehicles will far exceed the current commercial helicopter market. And that is why the development of new aircraft is essential not only to serve this large emerging market, but also to meet the needs of users and existing restrictions.

3.1. VTOL requirements for UAM

The general requirements and restrictions on which the design of this type of aircraft depends are various and, due to the fact that they are still in the development phase, new with respect to the design and needs of conventional aircraft. Although the concept of UAM is not something new (because, as already mentioned in the introduction, it is an idea that has been present since the beginning of helicopter operations around the 1940s) and it is becoming more and more concrete and accurate in some respects, the studies on the detailed requirements of these vehicles differ widely. The latter applies to the so-called top-level aircraft requirements (TLARs) of design range, number of seats and cruise speed. These aspects, together with the rest of the key elements for the design of a VTOL vehicle, are shown in the diagram in Figure 3.1.

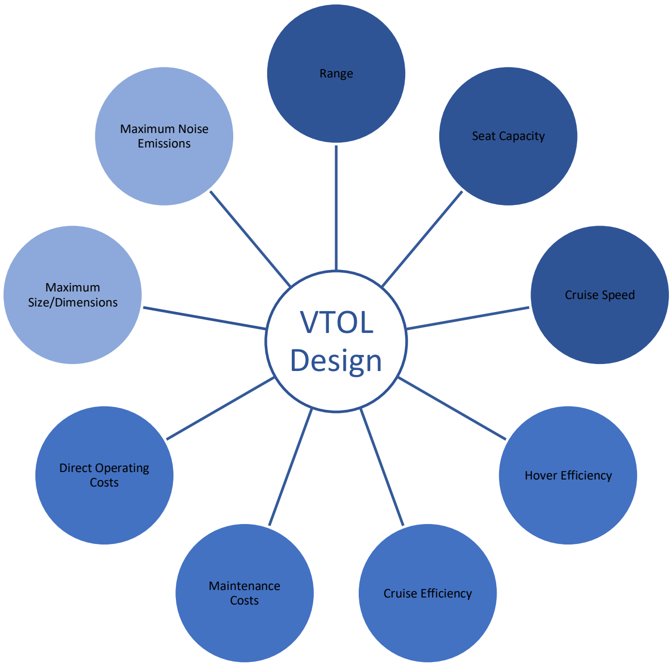


Figure 3.1. Fundamental requirements (in dark blue), external restrictions (blue) and other design parameters (light blue) involved in the design of VTOL vehicles (own elaboration based on [4]).

The composition and nature of the missions that the VTOL vehicles will carry out (and which will be explained in depth later in section 4) will play a very important role when defining these requirements, since they have a great impact when it comes to achieve a tradeoff in hover and cruise flight efficiency. The relative proportion of each of the flight phases totally changes the type of aircraft that is optimal for each mission.

In addition to these requirements, the successful implementation of VTOL vehicles in the urban and inter-urban environment depends on public acceptance, so sufficiently low noise emissions must be ensured. This aspect is not only translated in terms of the volume of the noise itself, but also in the type of noise. Studies on public perception of urban air mobility (UAM) indicate that the noise footprint left by VTOL vehicles should, as far as possible, be integrated within the existing urban background soundscape to ensure community acceptance, which numerically implies a noise level 15 dB lower than that of a conventional light helicopter [6]. This challenge requires early consideration in the design process, since the first approaches to reduce the noise level produced by VTOL aircraft are focused on spreading the thrust production in multiple rotors and increasing the effective area of these ones in order to reduce the speed of the blade tip (the determining factor in noise generation), however, this contradicts the demand for VTOL vehicles to be as compact as possible to cope with the limited space present in cities, so the size of this type of vehicles can also be a limiting factor for the performance of operations in urban areas.

3.2. VTOL designs and classification

The advances in electric motors, batteries and, above all, distributed electric propulsion (DEP) are the key element for the development of new VTOL vehicles. However, the concept of the DEP together with the capacity of these vehicles (autonomous vehicles are normally designed to transport one to five passengers) lead us to differentiate between different vehicle configurations depending on how the propulsion is generated.

Generally, this type of aircraft is classified into two large groups depending on the lift production during the cruise phase and the mechanism that allows the VTOL. However, as we can see in Figure 3.2, we can go further and make a more detailed classification within both groups depending on other factors such as propulsion distribution, thrust production, efficiency, noise level, etc. Next, in the following subsections, each of these configurations will be described in depth.

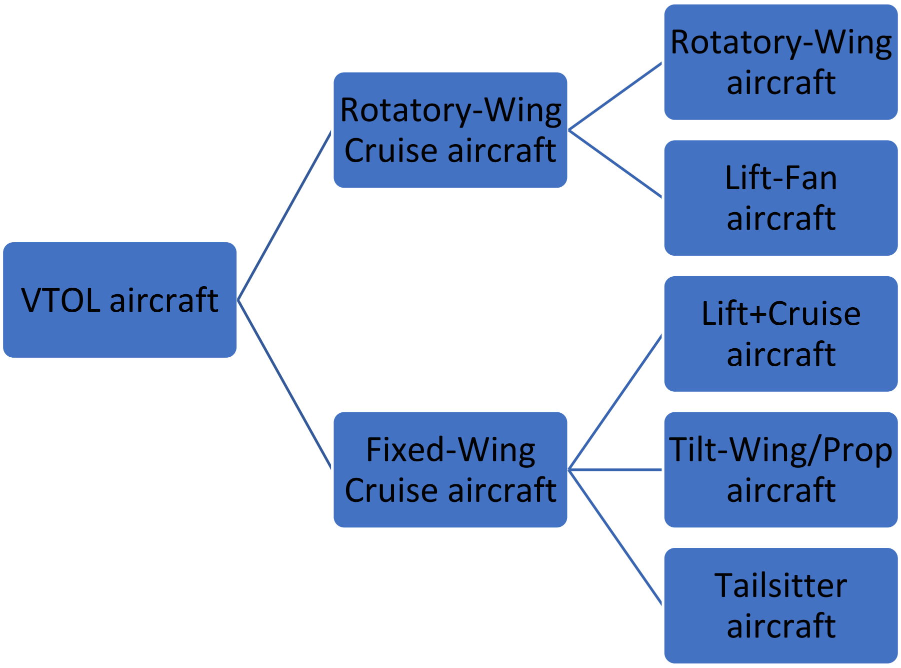


Figure 3.2. Representative scheme of the classification of VTOL aircraft [own elaboration].

3.2.1. Rotatory-Wing Cruise VTOL vehicles

Aircraft configurations belonging to the Rotary-Wing Cruise VTOL vehicles group are characterized by their speed and efficiency limitations during the cruise phase, so they present clear disadvantages in terms of range compared to other types of aircraft. However, they have very good responses in hovering and VTOL. These aircraft use the same thrusters for both VTOL maneuvers and cruise flight. Within this group, we can in turn classify the aircraft into two other subgroups depending on the size and location of the rotors: Rotary-Wing and Lift-Fan vehicles.

- Rotary-Wing aircraft are all those vehicles that are "more similar to big drones" so to speak, consequently it is understandable that every time we are told about UAM or taxi-drones the first configuration that comes to mind is this. Within this group, one can find different configurations of multi-copters and all kinds of conventional helicopters from which we can take advantage of part of their design, so this configuration is also the one with the least system complexity. However, as we can see in Figure 3.1, one of the key parameters for the design of VTOL vehicles is their general dimensions in order to integrate them into the urban environment, therefore, and with the aim of compensating the footprint due to large rotor areas, the rotors of this type of vehicles are normally placed in a stacked configuration. In the literature one can also find them as Wingless multicopters or Quadrotors according to articles and research carried out by NASA [1]. Examples of vehicles belonging to this group are the famous Volocopter 2X (one of the best known in the field of VTOL vehicles) and the LIFT Aircraft Hexa, as depicted in Figure 3.3. The latter draws attention, since it is a type of ultralight VTOL vehicle for personal use with capacity for a single passenger who is the same one that controls the aircraft.

- The other type of aircraft belonging to this subgroup are the so-called Lift-Fan vehicles, whose size is similar to that of a conventional car. This concept prioritizes the efficiency of operations in the limited space existing within the urban environment and therefore provides more compact dimensions, however, these aircraft are also less efficient than Rotary-Wing aircraft in terms of suspension. In addition, while embedded fans offer safety benefits during ground handling, achieving low enough noise levels will be a challenge for this configuration as, due to their small cross-section, the fans will need to rotate at larger speeds in order to provide the necessary thrust, which is associated with considerable noise emissions. An example of an aircraft belonging to the Lift-Fan vehicle set is the Neva AirQuadOne. Figure 3.4 illustrates a prototype of this vehicle.

a) Volocopter 2X at IAA 2017 [7]. b) LIFT Aircraft Hexa [8].

Figure 3.3. Two different configurations for Rotary-Wing Cruise VTOL vehicles group.

Figure 3.4. Prototype of the Neva AirQuadOne model [9].

3.2.2. Fixed-Wing Cruise VTOL vehicles

The first thing one must consider when studying Fixed-Wing Cruise VTOL vehicles is that the fact that their design has a fixed wing does not mean that they lack rotors to float. As mentioned earlier, advances in distributed electric propulsion (DEP) allow us to implement aircraft concepts capable of combining both VTOL flight and cruise flight based on a fixed wing, keeping complexity and weight parameters of the system at an acceptable level. While the Rotary-Wing Cruise aircraft are more similar to what could be a "large drone" capable of transporting people, within this group appear concepts that are closer to what could be a "conventional aircraft" of small dimensions. It is therefore that Fixed-Wing Cruise VTOL aircraft are much more efficient and faster during cruise flight compared to the concepts explained above. However, as the configurations belonging to this group present a significantly greater achievable range than those based on rotary wing for cruise, the hovering characteristics and the VTOL stage will be compromised, being less flexible when performing the takeoff and landing operations, since the intention to maximize efficiency in cruise flight is accompanied by a limitation in the design of large rotor areas necessary to maintain efficiency in the hover stage of flight.

Next, the three different types of aircraft that derive from Fixed-Wing Cruise VTOL vehicles will be described in depth depending on further characteristics in their design: Lift+Cruise aircraft, Tilt-Wing/Prop aircraft and Tailsitter aircraft.

- *Lift + Cruise aircraft* are all those VTOL vehicles that have two independent sets of propellers. One power gear is used only for hovering and vertical flight and the other power gear is used for only cruise flight allowing three different flight modes for this aircraft: helicopter mode with the lift rotors turning, compound mode with lift and thrust rotors operating simultaneously and airplane mode powered by the thrust rotors with the lift rotors stopped with the blade axis pointing along the longitudinal axis of the vehicle (in order to be aligned with free airflow and minimize air resistance). In this configuration, all the thrust generators are fixed and located in such a way that they produce thrust in the required direction, which, by not needing tilting mechanisms, considerably reduces the complexity of the system and results in an optimal design of all the rotors or propellers. As is to be understood within the category of vehicles in which this configuration is found, during the cruise flight stage one or several fixed wings will generate the necessary lift. Some real vehicle models that show this configuration are the Wisk Cora, the Aurora Flight Sciences Pegasus (see Figure 3.6) or the EmbraerX Eve, the latter presenting a capacity of up to 5 passengers.

- *Tilt-Wing/Prop aircraft*, also called vectored thrust aircraft, are the most ambitious and efficient configuration in terms of performance and noise within the world of VTOL vehicles. This design employs a tilt mechanism in order to orient all thrusters in the proper direction depending on the phase of flight the vehicle is in using the same propulsion system during all phases of flight. In this way, the rotors are optimized during cruise and VTOL flight while reducing both efficiency losses and noise caused by the propellers. Also, unlike other VTOL vehicle designs, Tiltwing aircraft incline the rotors during cruise in such a way that they generate less drag and weight penalty for the aircraft, resulting in a clear advantage to vehicle efficiency. However, this configuration requires a compromise in propulsion system design, as the tilt mechanisms necessary for the safe and efficient transition between vertical and horizontal flight add significant system complexity and additional weight, making it more difficult to bring a solid prototype of this vehicle to market. Representative examples of this configuration are the famous Lilium Jet (which is already in an advanced testing phase, having successfully passed its first test flights, see Figure 3.7), the Airbus A Vahana and the Joby S4.

- *Tail-sitter configurations* are similar to those previously explained as far as the propulsion system is concerned. This design also uses the same propellers for both vertical and cruise flight. Tailsitters enable VTOL flight by tilting 90 degrees not just the thrusters, but the entire vehicle. During takeoff, the vehicle is in a vertical position, with the nose of the aircraft pointing directly into the sky. After takeoff, the aircraft gradually banks toward level flight until it reaches an orientation suitable for cruise flight (see a performance schematic in Figure 3.5). This configuration does not require tilting mechanisms, however, the comfort of the passengers is the most restrictive element for the implementation of this design, since the complete tilting of the vehicle requires reasonable solutions to guarantee the comfort and well-being of the passengers. An example of a real tailsitter model is the Opener Blackfly, publicly unveiled in 2018 after nine years of long development [10].

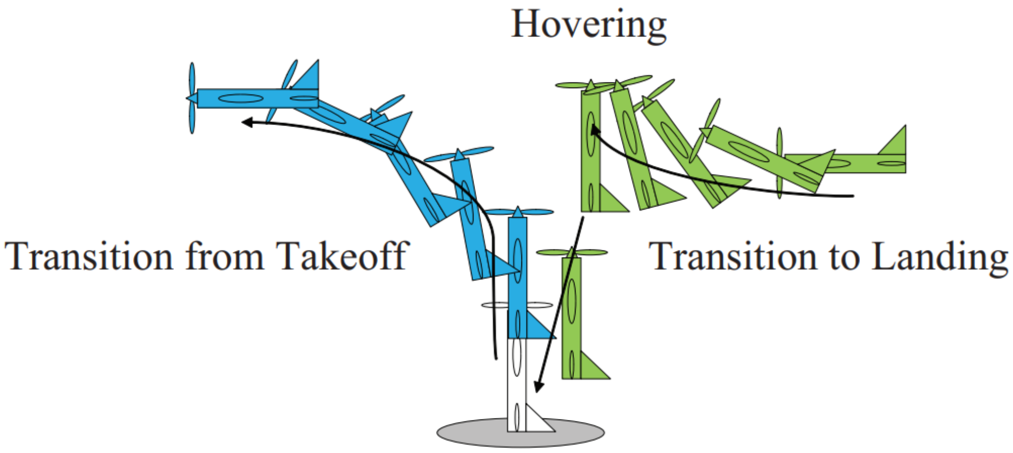


Figure 3.5. Scheme of the takeoff and landing of a Tailsitter VTOL aircraft [11].

Figure 3.6. Aurora Flight Sciences Pegasus successfully completing its first test flight [12].

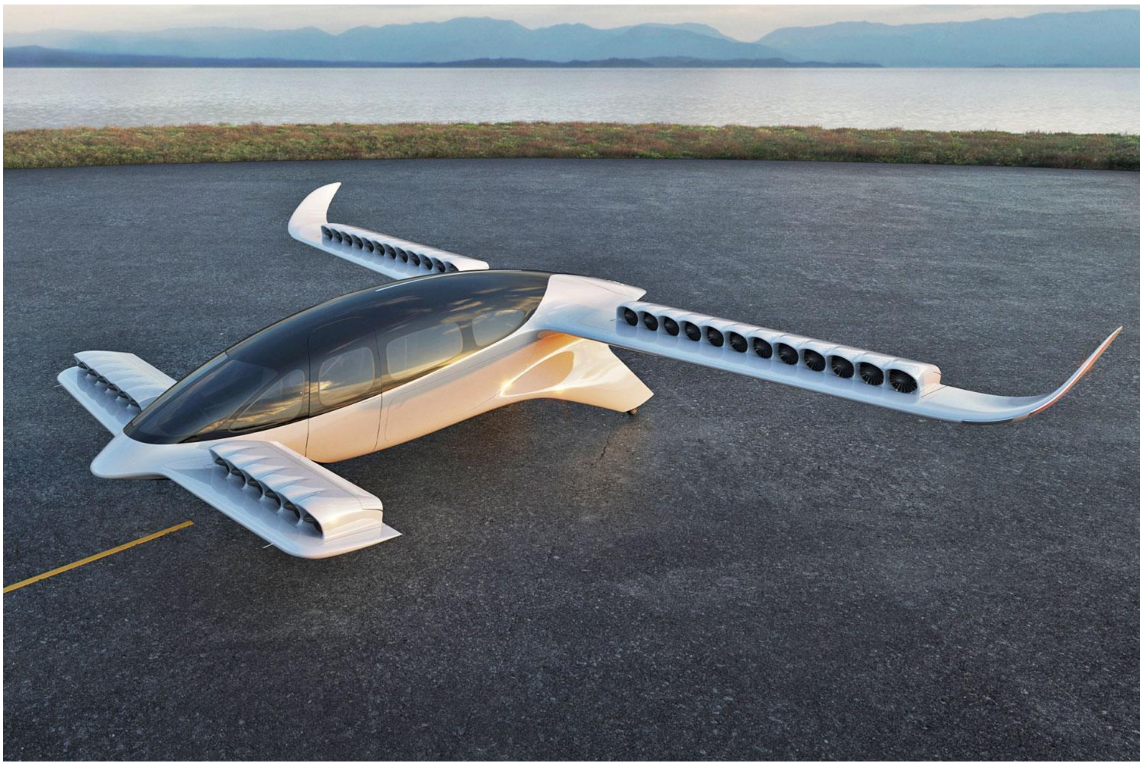


Figure 3.7. One of the 220 Lilium Jet eVTOL acquired by Azul Linhas Aéreas [13].

To end with the study of the different configurations of VTOL vehicles that have been developed since the appearance of the first helicopters, the Vertical Flight Society (VFS), an entity that provides a complete and detailed description of the different types of aircraft and which maintains a database with all the known designs of these types of vehicles, proposes a further subdivision of aircraft, the rotorcraft. Rotorcraft concepts include both electric helicopters and novel autogyros, that is, helicopters-like aircraft in which the rotor, instead of turning by the power of the motor shaft, turns by the force of the air that flows through it, generating forward propulsion by a separate propeller. In this project, given that this configuration is halfway between conventional helicopters and purely VTOL vehicles, it has been decided to classify them in a category apart from those previously analyzed, however, if they can exceed the requirements previously mentioned in Figure 3.1 and offer lower operational costs than conventional helicopters, rotorcraft will also be a configuration to consider in the context of UAM operations.

A representative example of rotorcraft designs is the Pal-V Pioneer flying car (see Figure 3.8), a notable model for the fact that it practically consists of a “flying car”. This rollable aircraft is capable of both being driven on the ground like a car and fly like an airplane, however, the Pal-V Pioneer is intended to be a personal use vehicle, not necessarily UAM [1].

Figure 3.8. Pal-V Pioneer flying car in both ground and flight driving modes [14].

4. VTOL vehicles missions

In order to understand how this type of vehicle will affect the airport environment and specify some of the requirements exposed in section 3.1, it is very important to define and understand the nature of the missions that they will carry out and start putting numbers in mind for their application in the real world. However, some agencies belonging to different fields of mobility and technology have already done this work for us, defining different types of missions to execute. These parties, also involved in the development of VTOL aircraft, are for example UBER, a company that provides transportation services that stands out for connecting passengers with vehicle drivers through a mobile application, and the well-known National Aeronautics and Space Administration (NASA), U.S. government agency in charge of aerospace research. Later, these missions will be analyzed in depth, but now we are going to focus on the trends and studies carried out on the UAM.

4.1. Context of VTOL vehicles missions

In the past, different missions have already been proposed in the context of urban air mobility, ranging from purely theoretical proposals to detailed design studies in conjunction with the development of real VTOL vehicles. These missions published in the UAM field are mainly [15]:

- Commuting to/from work or other routine trips around cities.
- Transfers from end to end of the cities that allow travelers to avoid city traffic and cross it in a short period of time.
- Shuttles that go from the cities to the airport or vice versa to provide faster connectivity to airline passengers.
- Subway-like services that connect passengers with other existing means of public transportation

In the previous list, of course, the great variety of missions for VTOL vehicles that have been published over time have not been included, but rather the main ones and those that would generate the greatest demand.

Below, in Figure 4.1, a compilation of the various missions proposed in the field of the UAM are collected in graphic form together with the number of passengers on board. Note that the value zero for both the number of passengers and the range indicates that there is no value specified for that parameter.

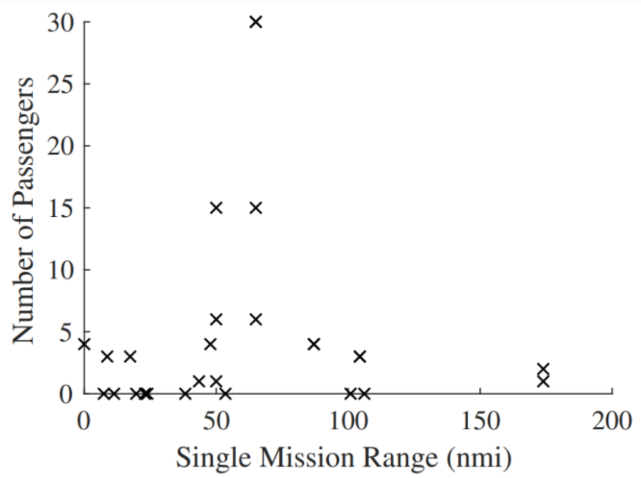


Figure 4.1. Summary of the ranges (in nmi) and number of passengers transported for UAM missions [15].

As we can see in Figure 4.1, most of the proposed missions have ranges of less than 100 nautical miles (nmi) with less than 8 passengers. The longest missions in terms of range reach 175 nmi and these are flights intended to go from the center to the end of a city or from a metropolitan area to surrounding rural areas or suburbs. Only three missions have more than 10 passengers, which is due to the current Federal Aviation Regulations (FARs) that will be used, at least in part, for the certification of many novel VTOL vehicles and that have stricter requirements for aircraft with more than nine passenger seats than for aircraft with, for example, seven to nine passenger seats. Additionally, under Part 135 of the FARs, an aircraft may be operated by a single pilot only if it is carrying nine or fewer passengers.

Regarding the taxonomy of the proposed missions, there are five different operating models for passenger transport, explained below from the most to the least on-demand:

- *Private operations*. Operations model in which a vehicle serves only a single person or party (such as a family unit) for a period of time greater than the duration of a single flight. This model has the characteristic that it is dedicated to the service of this individual or party and does not serve other clients between missions, that is, the vehicle that operates this type of model will be for personal use and, therefore, will need a space for park.
- *Air taxi.* In this service, a single user or group of users reserves the entire aircraft for an entire flight and determines the origin, destination and departure time of the flight.
- *Air pooling.* The air pooling model is a service where multiple individual users are aggregated into a single vehicle for flights. In this model, flight departure times and/or origin and destination locations can be defined in two ways: by a single user, where the rest of the users will have to adjust to that schedule, or by the operator to ensure an agreement among the passengers.

- *Semi-Scheduled Commuter*. In this semi-scheduled transportation model, flight departure times and/or departure locations are modified from a reference schedule based on consumer preferences. For example, an aircraft can be scheduled to depart from a certain location between 9 a.m and 11 a.m each day on a particular route, but the actual departure time will change from day to day depending on the preferences or availability of the group of passengers that will travel.
- *Scheduled Commuter.* The scheduled commuted model provides a near-on-demand service by offering frequent flights covering the same routes on a regularly scheduled service. This would be the model that most closely resembles "conventional" public transportation.

These operating models do not have to be directly linked to any of the missions listed above. Many of these missions can be carried out under any of the five operating models. To give an example, theoretically a connection flight to the airport could be carried out under any of these models, however, a “subway-like” mission of public transport is totally incompatible with the models of private property or air taxi.

4.2. NASA mission

NASA, for several years now, has been carrying out important research on aircraft and all kinds of operations in the urban air mobility environment, mainly conducted by the Revolutionary Vertical Lift Technology project (RVLT) where multiple VTOL aircraft designs have been developed such as those discussed in section 3.2 to somehow focus and guide research activities in support of aircraft development for emerging aviation markets.

In addition, the American information technology and management consulting company, Booz Allen Hamilton explored the market size and recognized in its study for NASA three different potential markets for UAM: Airport Shuttle, Air Taxi and Air Ambulance. In fact, the Airport Shuttle market is expected to be an early adopter of UAM due to its operational efficiency, however, before delving into these markets and the nature of their missions, it is worth highlighting the general mission profile that NASA proposes to be carried out by the VTOL vehicles in the missions of the different markets mentioned in the UAM environment (see the Annex to identify the procedure followed by the NASA team in order to create a representative standard scenario for the main cities of the US territory where this general profile is carried out). Each mission will consist of the segments illustrated in Figure 4.2 which are described below with each of their associated constraints:

1. *Taxi*. The general mission profile starts with a taxi segment, just like in commercial aviation, which can be performed in several ways depending on the aircraft design. In this segment, the vehicles could hover, power themselves while rolling on their wheels, or could be moved from a parking/loading area to the takeoff pad with some type of ground infrastructure (e.g., a tow vehicle). NASA proposes that each vehicle is

capable of rolling on its own wheels and, therefore, it must carry fuel/energy to drive a 15-second taxi ride at 10% of its cruise power.

2. *Vertical climb to 50ft*. After taxiing, the vehicle must take off vertically, climbing to a height of 50 ft above ground level (AGL) at a speed of 100 ft/min. This speed represents a rate of climb slow enough in order to be comfortable for passengers on board.
3. *Take Off Transition*. After vertical takeoff to 50 ft, the aircraft will transition to climb flight. This stage is necessary since for many VTOL vehicles (such as tilt-wing vehicles) there is a finite period of time in which the aircraft undergoes a configuration change from vertical to horizontal flight (when for example the rotors change orientation with its tilting systems). For this segment, NASA proposes a 10-second transition at maximum power.
4. *Climb*. After transition, the aircraft will climb to cruise altitude. To help ensure that the aircraft can both gain altitude and move away from the launch area quickly, NASA sets a climb rate of 900 ft/min at the beginning of the climb. If this rate of climb is maintained, the vehicle would reach an altitude of 500 ft AGL (which would place it above the airspace where UAVs may be operating) in approximately 1 minute after takeoff.
5. *Cruise*. After climbing to the desired altitude, which will be discussed below, the aircraft will enter cruise flight at the speed at which each vehicle maximizes its range (NASA does not propose a specific cruise speed). The length of the cruise stage will depend on each mission (depending on whether it is long or short range) taking into account that the actual distance traveled at cruise altitude must, of course, be less than the specified range. What NASA does specify is that, in order to guarantee sufficient maneuverability of the vehicle and the ability to fly higher if necessary (in case of contingencies in the airspace such as a potential risk of collision), the vehicle must be capable of flying at least a 500 ft/min rate of climb in this cruise segment.
6. *Descent Transition*. Following what would be the stage equivalent to descent in commercial aviation, for which NASA, far from specifying a particular profile, only specifies that aircraft must be capable of flying in the cruise segment until reaching the desired range from the takeoff location, the aircraft will enter a transition segment similar to that described above, except that in this case the aircraft must transition to vertical flight.
7. *Hover*. After transitioning to vertical flight, the aircraft must hover for 30 seconds at a height of 50 ft AGL before carrying out the vertical descent. This segment is added to allow for final pre-landing clearances, which may require a short hold, and to properly position the aircraft for landing.
8. *Vertical descent from 50ft and taxi*. The aircraft then performs the vertical descent from 50 ft AGL at a speed of 100 ft/min to land and, after landing, a final taxi segment which has the same requirements as described above must be performed.

NASA further specifies that aircraft must complete the overall mission profile with an additional 20 minutes of cruise added as a reserve. This segment is, of course, subject to the same restrictions as the main cruise segment of the mission. This reservation is based on existing regulations for rotorcraft operating under visual flight rules (VFR), which are specified in 14 CFR §91.151. VFR is assumed because the first operations of VTOL aircraft have been conducted under VFR and also rotorcraft regulations are assumed because the aircraft that will perform this mission will be capable of landing vertically like today's rotorcraft, which greatly increases the number of locations suitable for an emergency landing in the event of an off-rated situation in which the aircraft is unable to find a normal, designated landing location.

Additionally, these missions last around 20 minutes, which implies that the reservation of the aircraft would allow it to fly to an alternative vertiport.

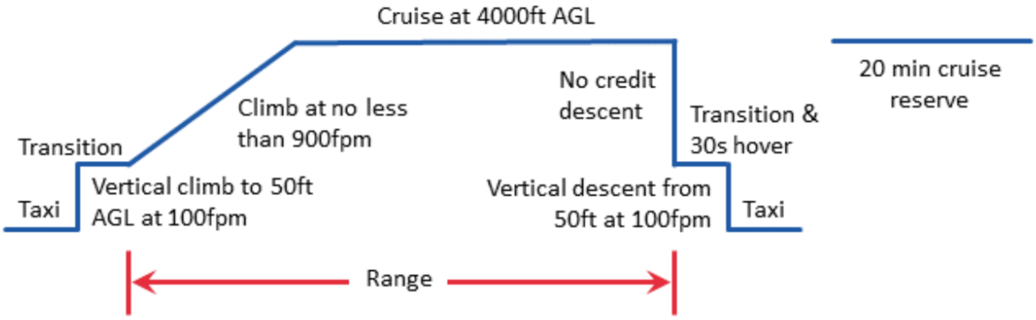


Figure 4.2. General mission profile proposed by NASA with all segments and their associated constraints specified [15].

Last but not least, as it was mentioned above, NASA specifies a nominal cruising altitude at which aircraft must fly on proposed missions. In choosing this altitude, two factors are considered: the first is that the duration of the flights is relatively short, so to ensure safety and efficiency levels of vehicle performance, the height should not be excessively high, since it would avoid an unnecessary waste of energy in climb and would provide safety in operations in the event of a flight contingency that requires an emergency landing. The second factor that must be taken into account is public acceptance (that is, minimizing the impact on the environment due to noise) and correct integration in the airspace management, which will dictate that aircraft must fly higher than the minimum operating altitude.

Existing FARs specify in 14 CFR §91.119 minimum safe altitudes for flying over congested areas. The rule stipulates that an aircraft must fly at least 1,000 ft above the highest obstacle in a horizontal distance of 2,000 ft from the aircraft, so heights of existing objects in potential areas where VTOL vehicles could operate must be considered.

From data extracted from Figure 4.3, a database that collects the heights of man-made objects above 499 ft AGL around the United States, NASA staff conclude with an altitude requirement for the cruise stage of 4,000 ft AGL. This number comes from the fact that, as can be seen in Figure 4.3, practically all man-made obstacles rise to a height lower than 2,000 ft AGL (measuring the highest one 2,064 ft), therefore 2,000 ft plus the 1,000 ft of vertical separation stipulated by the FARs make 3,000 ft AGL to which NASA adds another 1,000 ft of vertical separation to allow the correct and safe integration of VTOL aircraft in the existing airspace around metropolitan areas.

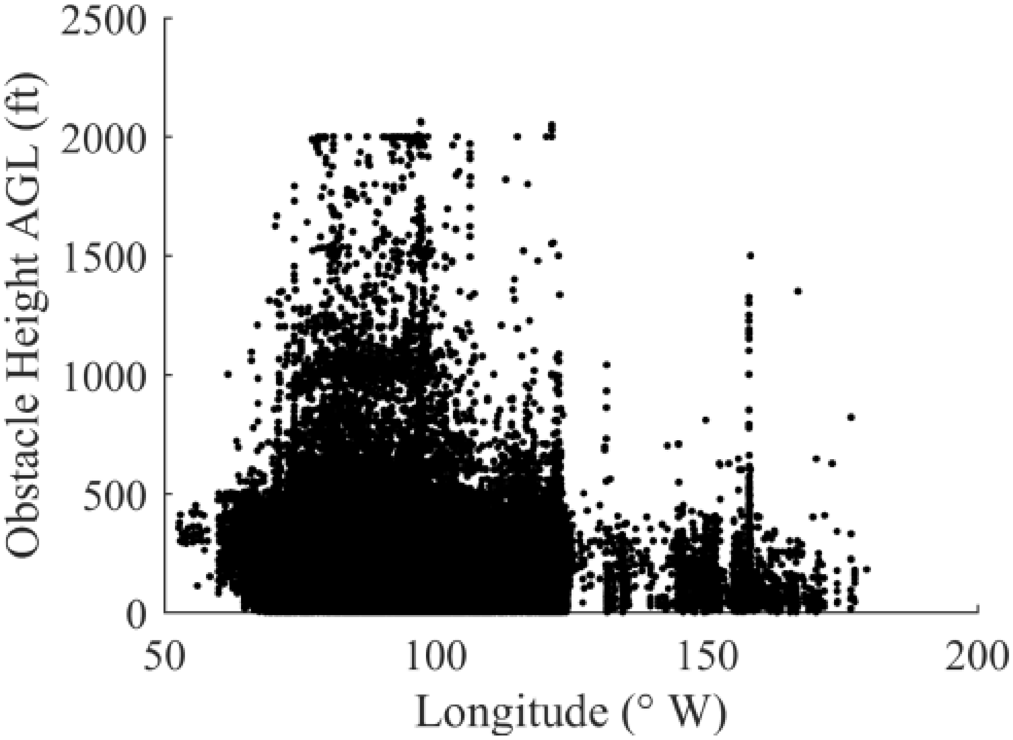


Figure 4.3. Graph with the heights of man-made obstacles over the United States (in feet AGL) [15].

4.2.1. Airport Shuttle and Air Taxi missions' analysis

Airport Shuttle missions include all those missions carried out by VTOL vehicles that are dedicated to transporting passengers to, from or between airports through fixed routes. The Airport Shuttle model somewhat resembles the Scheduled Commuter operating model cited above in that it is most similar to current public transportation options, such as subways and buses, with predetermined routes and regular schedules. The vehicles can be operated both autonomously and by a human pilot and can accommodate 2-5 passengers at a time with an average of 3 passengers per trip.

Air Taxi's service encompasses door-to-door rideshare (or individual) operations that allow customers to request VTOL vehicles to desired pickup locations and specify arrival destinations on rooftops in a given city. In this service, trips are not scheduled and are on demand, as is the case with current ridesharing applications (such as UBER or Cabify). As in the case of the Airport Shuttle, the vehicles can be operated either by a pilot or autonomously and can accommodate 2 to 5 passengers at a time with an average of 1 passenger per trip.

To correctly define the missions of Airport Shuttle and Air Taxi, it is important to first understand the concept of operations (or ConOps) designed to capture the activities performed by the passenger and by the vehicle to complete a mission. In Figure 4.4, a theoretical ConOps of a UAM service can be observed compared to the same trip made by a ground transport service. Passengers using the first one (i.e., Air Taxi or Airport Shuttle) undergo the following transfers: From origin to Vertiport by ground transportation, from Vertiport (closest to origin) to Vertiport (closest to destination), and from Vertiport to the destination location using ground transportation.

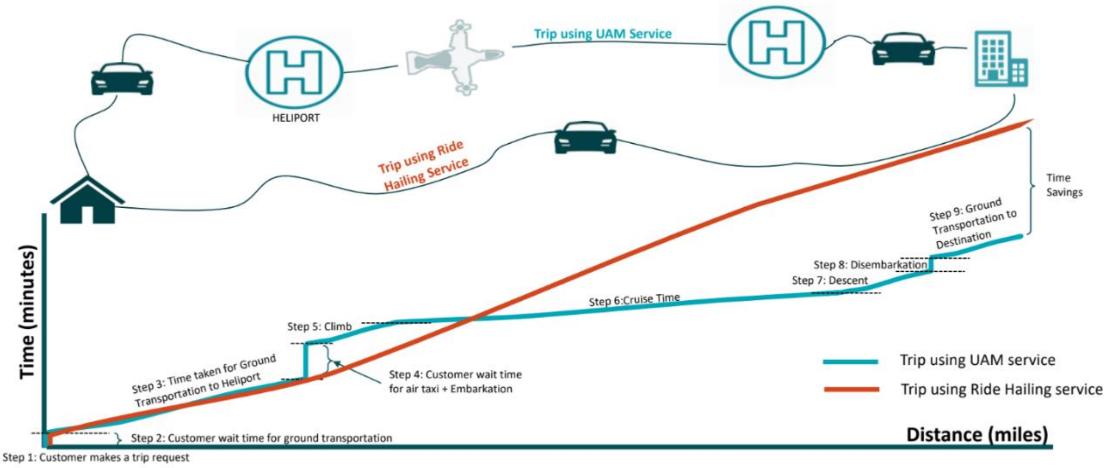
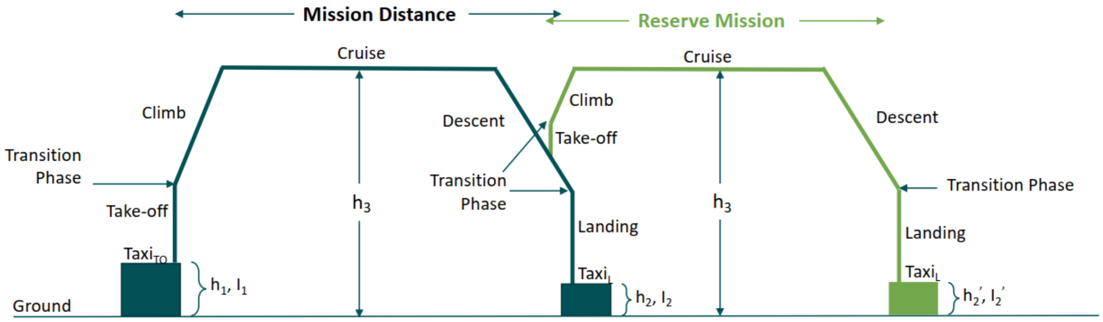


Figure 4.4. Theoretical ConOps for Airport Shuttle and Air Taxi mission compared with ground transport mission [16].

As far as the general profile is concerned, the Airport Shuttle and Air Taxi missions present a profile similar to the one in Figure 4.2 discussed above with the different flight stages already mentioned: taxi, climb, transition, etc., which in turn make up the five main flight phases: take-off, climb, cruise, descent, and landing. In Figure 4.5 we can observe this profile again together with a modeling of what would be the reserve mission (duration 20 minutes) that begins during the descent phase and follows a profile similar to that for the original mission, that is, takeoff, climb, cruise (at cruising altitude and speed), descent, and finally landing at another landing area.



Taxi: Preparation time to lift off once the passengers are on-board

Take-off: Climb vertically at hover power (no horizontal movement)

Climb: Climb to cruise altitude

Cruise: Flight phase that occurs when the aircraft levels after a climb to a cruise altitude and before it begins to descend

Descent: Aircraft begins approach to final landing. Has both horizontal and vertical component

Landing: Vertical landing at hover power (no horizontal movement)

where,
h_1: Height of take-off Site l_1
h_2: Height of landing Site l_2
h_3: Cruise Height
h_2': Height of landing Site l_2'

Figure 4.5. General mission profile of Airport Shuttle and Air Taxi mission [16].

4.2.2. Air Ambulance mission analysis

The Booz Allen team included in its study for NASA an Air Ambulance service as a potential market in the field of UAM since, despite its complexity in terms of the technical capabilities required on board the vehicles, in addition to many other legal and regulatory barriers, it is a service that is expected to have very good public acceptability. Air Ambulance's service includes trips to/from the hospital for emergencies and potentially hospital visits, which would expedite the transportation of patients to the hospital, resulting in vital health benefits.

Currently, the ambulance industry provides transportation and medical care to patients by land or air, and vehicles equipped with life-saving equipment operated by medically trained personnel in the US can be classified as: Ground Transportation (normally used for short-distance patients transportation from the scene of the emergency to the hospital), Helicopter or Rotary Wing (also used for short-distance transport of patients from the location of the accident or emergency to the hospital) and, finally, Fixed Wing Airplanes (used typically for transporting patients over long distances, usually across countries or oceans). Typically, the missions carried out by these types of ambulances (remark that, for this study, the concept of ambulance does not refer only to the land vehicle but to any vehicle, land or air, that allows the transport and medical care of patients) consist of the following stages graphically represented in Figure 4.6:

- Dispatch: time interval from call received to the unit notified by dispatch.
- Chute: time interval between 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 between unit arrived on scene to unit left scene.
- Transport: time interval from unit left scene to patient arrived at destination.
- Return: time interval between unit left destination to unit back in service.

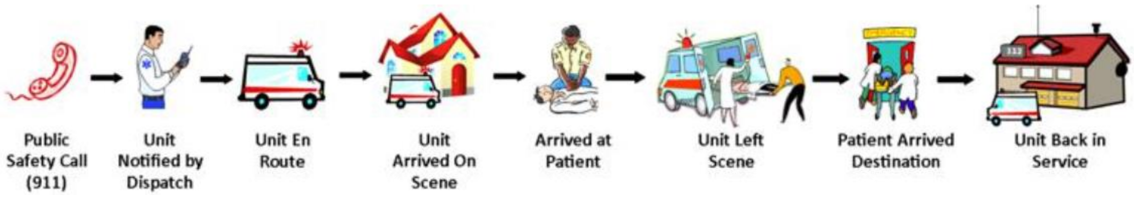


Figure 4.6. General Ambulance mission steps [16].

The objective of introducing VTOL vehicles in the ambulance industry is to reduce the total transport time of the patient, which is defined as the time interval between the notification of a unit for dispatch to the transport of the patient to the nearest hospital, since the only stages that can be expedited using faster vehicles are: Scene Response, Transport and Return time intervals.

In Figure 4.7, one can see a diagram of the three submissions that a general Air Ambulance mission typically consists of: Response (A-F), Transport (H-M) and Return to Service (N-R). For each of these three submissions, it is assumed that the profile to be followed is the previously mentioned for Air Taxi and Airport Shuttle shown in Figure 4.2 and Figure 4.5 (i.e., taxi, vertical climb, transition, climb, cruise, etc.) and for the fourth submission (Scene) the Air Ambulance is considered to be in Taxi mode. In an Air Ambulance mission, the total flight time consists of the sum of the response, transport and return times. Once the patient is transported to the hospital, the vehicle returns to its base (N-R) and prepares to return to service (R-Q). For VTOL vehicles, this time in which they prepare to return to service (also called preparation time) refers to the time required to recharge the aircraft's batteries for the next mission.

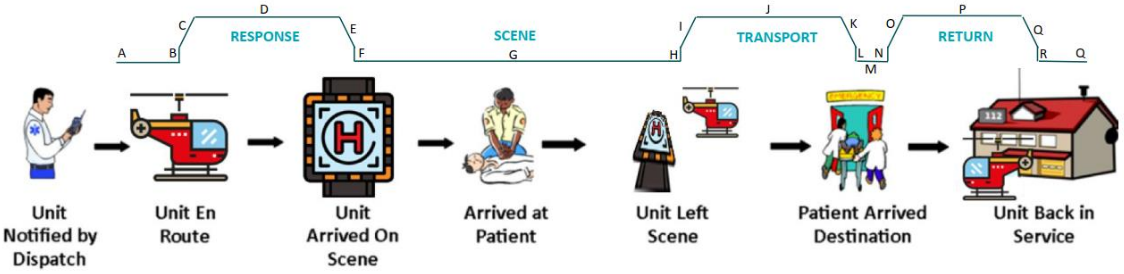


Figure 4.7. General Air Ambulance mission profile [16].

5. VTOL vehicles integration into the airport environment

Understanding the nature of the missions that the VTOL vehicles will carry out together with the different designs of these that exist (although some are still in the testing phase) currently, the next step to be carried out in this study is the integration of these vehicles in the existing airports. To do this, it must be ensured that UAM operations are compatible with existing conventional aviation operations without compromising in any case neither the air traffic controller workload (established as the main barrier in the integration of UAM operations in visual conditions) nor the minimum separation (proposed as the main barrier in the integration of UAM operations in instrumental conditions). In addition, efforts to integrate UAM operations in airport environments must be focused on applying the least possible changes to conventional aviation operations in order to ensure maximum performance for both. Altering current procedures for larger aircraft can be financially costly and politically intractable. Apart from this, many large airports already regularly experience problems associated with capacity (a notorious example is San Francisco Airport due to weather problems caused by fog) so it should be noted that the option to reduce throughput of commercial flight operations is totally unfeasible.

Throughout this section, the framework for the integration of unconventional operations (carried out mainly by helicopters or small planes) at airports will be briefly introduced, which serves as background to lay the foundations for the integration of the UAM itself in this environment giving examples of airports that, at present, already combine conventional operations with operations carried out by helicopters or by general aviation. Put in context, the main drawbacks and restrictions in the integration of UAM operations in airports where their performance will be conditioned mainly by the capacity of the runways will be assessed and, finally, the analysis of five different operational schemes at a theoretical level found in the literature will be detailed with its main advantages and disadvantages, which will offer a closer approach in the implementation of the UAM at the airport level.

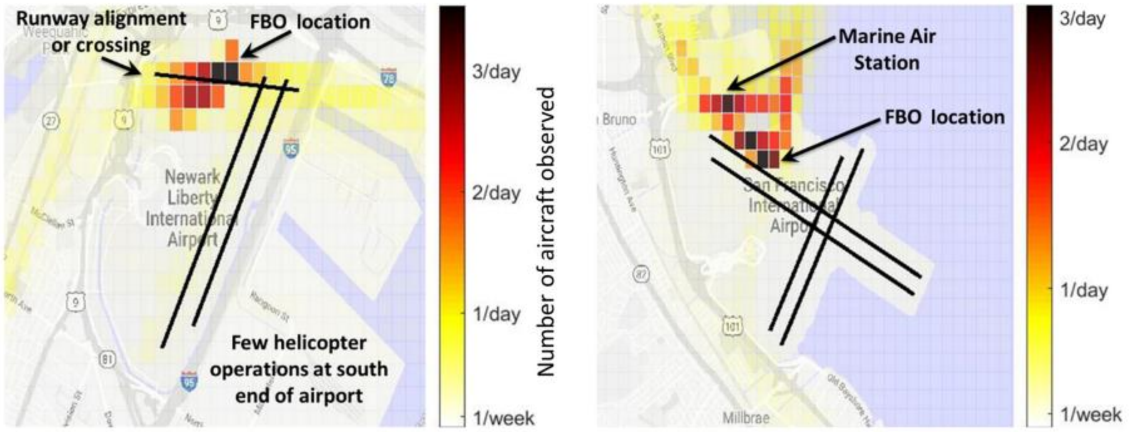
5.1. Background and current trends

The idea of combining VTOL vehicle operations with those of conventional aviation at airports is not relatively new. At major airports, helicopters have been operating since the 1960s. A clear example are Chicago Midway International and O'Hare International airports, which in 1960 supported a total of 50,000 helicopter operations (which translates into an average of 135 flights per day). The efforts in those years by airlines and aviation companies were focused on the development of approach and departure procedures for all types of weather that, in no case, conflicted with conventional flights, for which the FAA developed several strategies including, among others [17]:

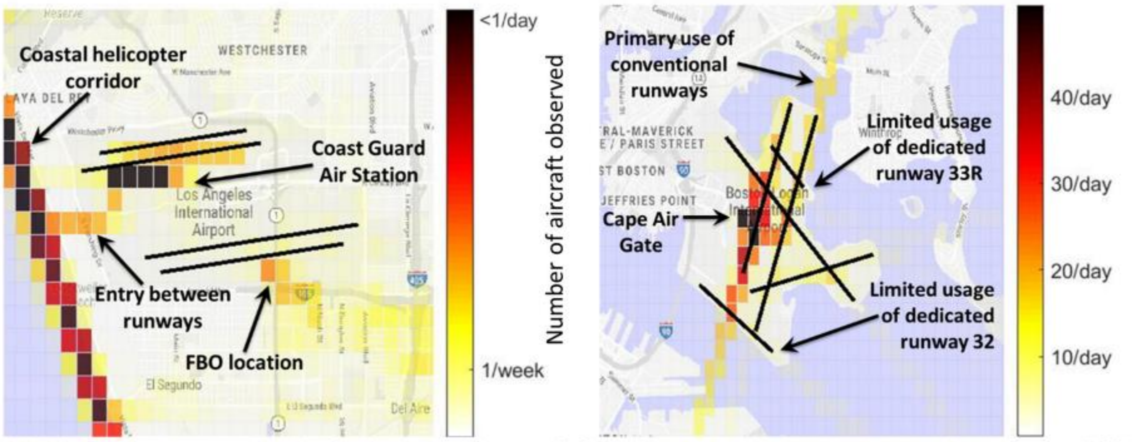
- Design of TOLAs (TakeOff and Landing Areas) for helicopters located separately from the active runways.
- Design of helicopter routes that avoided conflicts with the arrival and departure procedures of conventional aviation.
- Assignment of an air traffic controller and a radio frequency for helicopter operations.
- Reduction of the separation minima between helicopters and commercial aircraft.
- Authorization of a two-way travel on helicopter routes with 500 ft of lateral offset from the centerline.

In addition, two decades later, Ransome Airlines achieved non-interfering VFR shuttle flights to major airports through STOL (Short TakeOff and Landing) aircraft, navigation systems, and steeper arrivals at inactive runway ends.

These historical operations of helicopters and small aircraft in conjunction with the operations carried out today by helicopters at some airports provide initial information on the integration strategies for the UAM. According to FAA air traffic databases between 2016 and 2018, the 30 largest airports in the United States received an average of 48 general aviation (GA) flights per day [17]. It is worth mentioning here that general aviation corresponds to all the activities belonging to civil aviation that do not correspond to the routes established by the airlines, whether they are regular or charter flights. The ATC strategies currently used to manage these flights represent a starting point for the subsequent integration of the UAM. In Figure 5.1, a heat map of GA and helicopter flights below 1000 ft AGL can be seen for Newark (EWR), San Francisco (SFO), Los Angeles (LAX), and Boston (BOS) airports. Analysis of these data helps to identify the air infrastructure and flight paths used for the integration of helicopter and GA flights in the airport environment.



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



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

Figure 5.1. Heat map of GA and helicopter operations below 1000 ft AGL for 180 days of radar data between 2015 and 2016 for EWR, SFO, LAX and BOS airports (Note: FBO = Fixed-Base Operator) [17].

As can be seen at LAX and SFO airports, most helicopter operations fly directly to helipads or aprons located at the operator's fixed base. These flights in no case cross the runways or interact with conventional procedures. On the other hand, helicopter flights at EWR and BOS airports are primarily to, from, or over runways. GA and commuter operations share the runways and conventional procedures at almost all these airports, except for BOS, which has two independent runways for small aircraft operations (33R and 32), although limited for VFR and a single wind configuration, resulting in a very low utilization.

As shown in the cases of the SFO and LAX airports, helicopters provide great flexibility both in the design of approach and departure procedures and in the location of TOLAs. In addition, ATC policies offer special subsidies to helicopters that meet certain performance characteristics (reduced ground roll, flexible glideslope and climb angles, reduced approach speed, etc.) to cause the least possible impact on conventional airport operations.

It is clear that VTOL aircraft have similar characteristics and performance to those of conventional helicopters, however, it is still unknown if these vehicles will be properly classified as helicopters and will be granted the same ATC assignments, so this study is carried out at the theoretical level assuming this statement as true.

5.2. Constraints for UAM Airport Interoperability

In the same way as in conventional aviation, the performance of UAM operations in the different airports where they are going to be introduced will be limited by the capacity of the runways, therefore, to support these flights, both efficiency of the existing runways must be increased as much as possible such as siting new TOLAs specially developed for the UAM. The interoperability of UAM operations on existing runways and the location of new TOLA infrastructure depends primarily on three ATC-related attributes [17]:

1. *Separation minima*. Air traffic controllers must provide, in the terminal airspace, a specific distance, time or height between some aircraft and others or between aircraft and the different existing obstacles. Within the separation measures, two types must be ensured: a longitudinal separation that refers to the distance that an aircraft must maintain to minimize wake vortex interactions, conflicts in the air or runway occupancy violations, and lateral separation that limits how closely aircraft can operate simultaneously on procedures or runways. Of this attribute, it should be noted that the longitudinal separation measurements are those that generally establish the performance capacity of a given procedure or TOLA, while the lateral separation measurements indicate the location of the runway and the procedures.
2. *Controller workload*. ATC is a human-centered, voice-based activity in which the air traffic controller's workload is proportional to traffic volume, airspace complexity, and communications requirements, among other factors. Therefore, if the pertinent measures are not taken for their management, the UAM operations of access or egress to the airports where they operate will be affected by a delay if the workload capacity of the controllers is saturated. This occurs when the cognitive load on controllers exceeds their personal comfort level in providing the required ATC services. Controller workload is expected to be the ATC attribute that most restricts the performance of UAM operations at airports under VFR. Options to ensure that this performance is not affected include opening positions for additional controllers in the control towers or, alternatively, reducing the amount of time a controller spends on an individual UAM flight by developing visual procedures, allowing pilots to visually self-separate, and utilizing data link communications to minimize voice communication requirements.
3. *Communication, navigation, and surveillance*. To support airport operations, specific navigation aids, radar systems and frequency spectra are used today. As far as UAM airport operations are concerned, four different communication, navigation and surveillance (CNS) systems can affect its scale. These systems are:

- Automatic Dependent Surveilance-Broadcast (ADS-B). A study conducted by NASA showed that the ADS-B system could support 1,400 or more small, unmanned aircraft below 400ft in a metropolitan area without frequency saturation using a low power setting. Although it is clear that UAM operations will take place above 400ft, the trade-off between flight speed, vehicle density and power configuration provides enough flexibility to manage ADS-B frequency saturation, therefore, this system is not expected to restrict UAM operations.
- Radio frequencies. Although high-volume UAM operations lead to radio frequency congestion, studies by NASA conclude that these can reduce the frequency of use in the short term through simplified route clearances, and in the long term, digital communications will be relied upon instead of traditional voice frequencies.
- TCAS. The UAM approach and departure procedures at airports must not, under any circumstances, activate TCAS alerts for conventional aviation. For this, in the airport environment, UAM operations must remain below 1000 ft or diverge from conventional aircraft during departures.
- Performance-Based Navigation (PBN). PBN provides several opportunities to reduce both separation requirements and controller workload for UAM.

5.3. UAM integration through theoretical operational schemes

Once the main barriers in the integration of UAM operations in the airport environment have been analyzed, and placed in the context of the current operations carried out by helicopters and other small-sized aircraft at the main airports which establish an important starting point for the implementation of the UAM, a topological framework found in the literature of the runway infrastructure and the flight procedures required for the integration of the UAM services in a purely theoretical airport will be analyzed. This framework, which can be seen in Figure 5.2, represents five different operating schemes depending on the distance and orientation of the TOLA to be used in UAM operations with respect to the runways and conventional procedures of the theoretical airport.

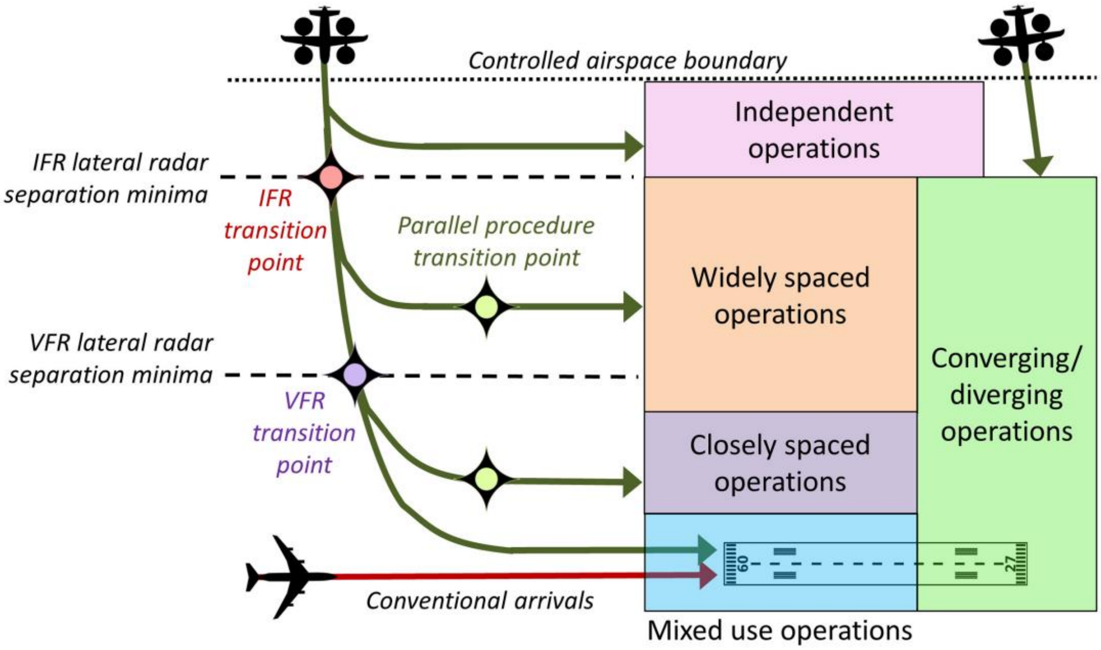


Figure 5.2. Topological colored framework of five different operating schemes for UAM TOLAs sited at airports or their vicinity [17].

As one can see, each operating scheme has a region (marked in different colors for each case) where the TOLAs should be located. These will experience similar procedures and operational restrictions depending on the region where they are located.

The three transition points marked in the figure represent the locations where the type of separation applied between VTOL vehicle arrivals and nearby conventional aircraft should be changed. These points are the following ones:

1. *IFR transition point*. Arrivals of UAM flights that cross the IFR transition point will invade the minimum IFR radar lateral separation required for a conventional aircraft. Therefore, to avoid a loss of separation, measures such as flight guidance by a controller, the introduction of the vehicle in a required navigation performance (RNP) approach procedure or other types of separation measures must be applied.
2. *VFR transition point*. As in the previous case, arrivals of UAM flights that cross the VFR transition point will invade the minimum VFR radar lateral separation required for a conventional aircraft. To avoid loss of separation, after this point the controllers must guide the vehicle in question or visual separation must be applied.
3. *Parallel procedure transition point*. This point denotes the place where UAM aircraft enter the final approach (it would be a kind of Final Approach Point applied to UAM procedures). Once past this point, procedure-specific separation requirements must be applied.

In the following subsections, each of the five operating schemes previously shown in Figure 5.2 are defined in order to analyze the feasibility of supporting UAM operations in TOLAs located at or near airports.

5.3.1. Mixed UAM and conventional aviation on a shared runway operating scheme

In the mixed-use operations scheme (marked in blue in Figure 5.2), vehicles operating in UAM and conventional aircraft operate on the same runway, which requires an air traffic controller to combine the operations of both types of aircraft ensuring the necessary separation between them. Although in theory this scheme is a good starting point for the integration of UAM operations at airports since it does not require a new runway infrastructure, the fact of mixing conventional operations with operations of other types of vehicles (i.e. VTOL vehicles) poses several challenges, such as:

- The proximity of VTOL vehicles to wake vortices generated by larger aircraft.
- Performance limitation of UAM operations due to conventional aircraft operating tempo.
- Interaction of VTOL and conventional aircraft on shared runways and taxiways.
- Heterogeneous aircraft performance due to differences in their characteristics.

Despite these limitations, VTOL vehicles operating under VFR rules (especially if they are finally certified as helicopters) can use visual separation to adapt to wake vortex separation requirements and operate in conjunction with commercial flights. However, UAM operations under IFR standards cannot be carried out in this operating scheme without a performance reduction of commercial operations, since in IFR the wake vortex requirements cannot be met by visual separation.

5.3.2. Closely spaced operations operating scheme

In the closed spaced operations scheme (marked in purple in Figure 5.2), VTOL vehicles operate in TOLAs located relatively close to the conventional runway(s) so that, compared to the previous scheme, this one offers an increase in the performance of all operations, since it allows conventional and UAM maneuvers to be carried out simultaneously. However, this is subject to various operational restrictions and increased controller workload.

For operations under VFR regulations, a lateral separation of between 700 ft and 2,500 ft from conventional flights is necessary and, more importantly, UAM flights must be sequenced with conventional flights both on arrivals and departures to avoid problems associated with wake vortex. In approach procedures, it must be ensured that the largest aircraft do not pass the VTOL vehicles and in departures, which are even more restrictive, UAM aircraft must wait a certain time behind conventional aircraft until the wake vortex footprint completely dissipates. The need for this sequencing means that the controller workload is additionally increased and that UAM operations are dependent on conventional operations.

Flights operated under IFR regulations in this operating scheme must ensure a separation of between 700 ft and 9,000 ft from conventional flights, however, for simultaneous arrivals with a separation of less than 2,500 ft, very precise lateral and longitudinal spacing between the VTOL vehicle and the conventional aircraft is required (which increases the controller workload) and, in addition, UAM aircraft is required to operate at an approach speed similar to that of the largest aircraft, which makes this configuration totally unfeasible to implement. However, for IFR arrivals with a separation between 3,000 ft and 9,000 ft, neither precise spacing measurements nor similar approach speeds are required, but three additional controllers must be responsible for supervising the new TOLA of this scheme, as must be advanced radar required. Finally, to mention that arrivals under IFR at closely spaced TOLAs will cross, as we can see in Figure 5.2, the IFR transition point, which will violate the radar's lateral separation minimum. Nevertheless, duly equipped VTOL aircraft will be able to take advantage of the capabilities of established on RNP (EoR) as an alternative form of separation, thus reducing the controllers’ workload in this last segment.

Regarding the connection of the passengers’ flow coming from UAM flights with the airport terminal building, this operational scheme offers quick access for VFR operations since the flights begin and end in areas very close to the terminals (in heliports practically located with respect to these), however, it is more complicated to integrate IFR operations, especially when the minimum separation exceeds 3,000 ft.

5.3.3. Widely spaced operations operating scheme

The widely spaced operations operating scheme (marked in orange in Figure 5.2), is characterized mainly by the fact that the distance between the TOLAs and the conventional runway(s) is large enough so that the wake vortex does not affect UAM operations. This scheme therefore facilitates, from the point of view of the ATC, the integration of the UAM in the airport environment since, unlike the previous operational scheme, it is not necessary to sequence the UAM operations with the conventional operations or use advanced radar systems. However, the main disadvantage of this scheme is that the flexibility in the positioning of the TOLAs is negatively affected, in addition to complicating the rapid connection of UAM passengers with the airport terminals.

In this scheme, UAM flights operating under VFR must maintain a separation of at least 2,500 ft with respect to active runways and, once the VFR transition point has been crossed on arrivals, visual separation by the on-board pilots must be applied.

IFR arrivals that operate in this scheme must keep a minimum of 9,000 ft with respect to conventional flights, while departures, on the other hand, only require a minimum separation of 2,500 ft. In case UAM vehicles use EoR procedures, air traffic controllers are not required to provide sequencing or separation services, thus minimizing their workload.

In this operational scheme, the main implementation challenge at airports is the location of the TOLAs and their connectivity with the terminal buildings. As previously mentioned, the fact of carrying out operations widely separated from conventional airport operations and runways complicates and greatly slows down the connection between the place where UAM flights are carried out and the terminals from which they depart or to where the passengers go, so, in order to expedite the flow of passengers, the terminal accessibility (defined as the time that elapses from when the aircraft starts the taxi from the TOLA to the gate until the passengers arrive from the gate to the terminal building and vice versa) must be improved using various passenger transport vehicles (such as buses or cars that are already used today). In addition to ground transportation, a promising approach would be the use of air taxiing to further reduce the transfer time of passengers from TOLAs to terminal buildings, especially when the distance between them is greater. A VTOL air taxiing is treated like a ground taxiing aircraft, so it is not necessary to establish any type of airborne separation. However, air taxiing operations must be carried out within the lateral limits of the airport boundary. In order to reduce the limitations of air taxiing and energy consumption in air taxiing flights over long distances, the so-called point in space (PinS) approach is defined. In the PinS approach, the aircraft flies to a missed approach point (MAPt) located at a specified distance above the airport surface (without any TOLA physical infrastructure below) from where the UAM flight transitions to visual flight (if weather conditions permitting) and continue like this until reaching the airport gate. In Figure 5.3 a comparison can be seen between what a conventional passenger connection (scheme on the left) would be where the UAM aircraft arrives to a physical TOLA and then the passengers are transferred to the airport terminal gate either by air taxiing or by ground transportation services and the application of the PinS concept (scheme on the right) where the UAM vehicle arrives at the MAPt and continues to the airport gate through visual flight or air taxiing.

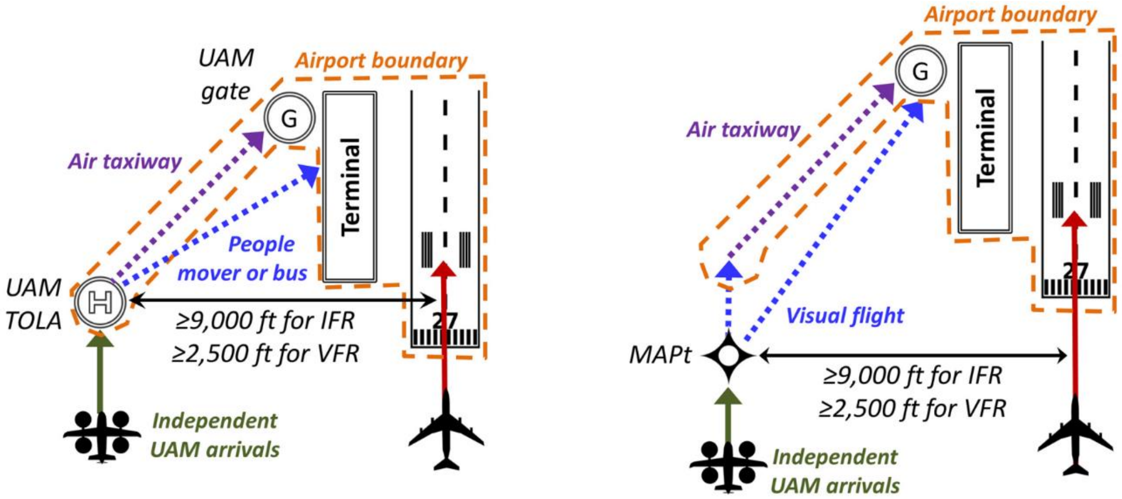


Figure 5.3. Comparison between a widely spaced IFR arrival using air taxiing or ground connections to the terminal from the TOLA and a widely spaced IFR arrival using the PinS concept [17].

5.3.4. Independent operations operating scheme

In the independent operations operating scheme (marked in pink in Figure 5.2), UAM flights will operate, as their name suggests, completely independently of conventional flights and the procedures of the airport in question. Conducted above the IFR transition point, independent operations will never violate IFR or VFR lateral radar separation minima.

In this operating scheme, a controller monitoring all the arrivals and departures of the TOLA where VTOL vehicles operate is necessary.

The main disadvantage of the independent operations operating scheme is the wide separation that must be provided between the TOLA and the airport or between TOLAs so that UAM operations can be carried out. This factor, if it is disproportionately large (that is, from 5 km upwards) can very negatively affect the performance of UAM operations since the TOLA-terminal building connection via air taxiing or through long-distance PinS visual segment may not be authorized by ATC (because it would be necessary to establish some type of airborne separation) in addition to being unfeasible from the perspective of UAM performance and energy consumption, so passengers would have to be transferred from the TOLA to the airport gate (and vice versa) by land vehicles in a less agile and fast way.

5.3.5. Converging and diverging operations operating scheme

In the converging and diverging operations operating scheme (marked in green in Figure 5.2), UAM traffic arrives or departures TOLAs located at an angle, or intersecting with conventional runways, which entails various benefits for the integration of VTOL vehicles in conventional airports associated with air traffic management by ATC, among others:

- Possibility, when dealing with divergent infrastructure, of simultaneous IFR or VFR departures from closely spaced runways without having to apply wake vortex separation (UAM departures that diverge by at least 15º with respect to conventional runways are totally exempted from any kind of wake vortex requirements).
- Ability, when it comes to convergent infrastructure, to carry out IFR or VFR arrivals (even if they are connected to closely spaced runways) without the need for additional controllers to monitor trajectory conformance.

However, despite these advantages, the implementation of convergent arrivals under IFR rules may be subject at some airports to procedure design requirements in order to avoid affecting the already established conventional procedures.

For the integration of convergent UAM arrivals at conventional airports, two concepts of operations found in the literature for VFR and IFR can be applied. These procedures combine part of the UAM approach procedures with part of the existing conventional approach procedures.

The first concept is Land And Hold Short Operations (LAHSO). Converging VFR arrivals to non-intersecting runways can be accomplished by visual separation, however, if flight paths cross, wake vortex separation is required [18]. The LAHSO concept allows VFR operations to be carried out simultaneously on crossed runways (i.e. runways that physically intersect) with the advantage of allowing UAM landings on existing crossing runways without affecting the performance of conventional aircraft or requiring additional controllers. As we can see in Figure 5.4 (left schematic) UAM and conventional landings would be sequenced as follows with the LAHSO procedure:

1. Both aircraft (conventional and UAM) approach to converging-intersecting runways to land.
2. The conventional aircraft lands and continues its go around path while the preceding UAM flight remains a period of time before the crossing point to avoid possible effects due to the wake left by the larger aircraft.
3. The UAM flight follows its landing course and goes around visually.

On the other hand, the Simultaneous Converging Instrument Approaches (SCIA) concept allows UAM flights operating under IFR standards to land on converging (but never intersecting) runways without the need to be coordinated with conventional flights. However, to always maintain safety in the operations, the following restrictions must be taken into account:

- The missed approach paths of the procedures (both UAM and conventional) cannot overlap at any time.
- Up to MAPt, lateral IFR radar separation between flights must be maintained.

- Aircraft pilots are responsible for visually avoiding each other in the event of a simultaneous go-around by both aircraft.
- The MAPt of each approach procedure must be separated by a distance of at least 3 nmi between each other.

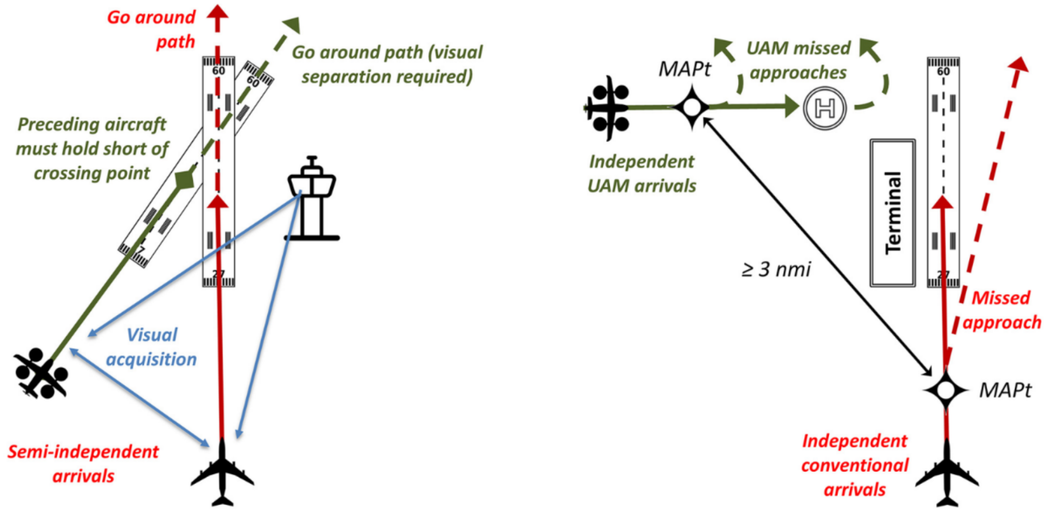


Figure 5.4. Procedures of two converging concepts for both VFR and IFR UAM arrivals integration into the airport environment (LAHSO, in the left and SCIA in the right) [17].

Regarding TOLAs location and terminal accessibility, this operational scheme greatly facilitates the siting of TOLAs at or near the airports since the LAHSO procedure allows UAM aircraft to use existing crossing runways and the SCIA concept allows UAM IFR flights land at TOLAs located near the airport terminals. In addition, the concept of divergent departures provides numerous advantages in these aspects since allowing departures (both VFR and IFR) from closely spaced infrastructure simultaneously with other flights without requiring wake vortex separation allows TOLAs ubication to be flexible.

6. Infrastructure required to support UAM operations

The term vertiport (from vertical and port) refers to the new spaces destined for the takeoff and landing of VTOL vehicles, that is, it includes both the platforms or areas from and to where the takeoff and landing operations are properly executed (TOLAs), such as the necessary infrastructure to support this type of aircraft (parking areas, battery recharging, etc.). All this infrastructure is designed to help in the mobility of people, providing them with an efficient and sustainable option.

Vertiports offer an opportunity to link different means of passenger transport using available resources in a rational way, so thinking of designs that use existing infrastructures adapted for UAM operations is the best way to integrate this type of mobility into the urban and airport environment and reduce its socio-environmental and economic impact. That is why the efforts throughout this section will be aimed at relating the theoretical operating schemes previously analyzed in section 5 with respect to the airport infrastructure necessary for VTOL vehicles to operate correctly.

This section will start with a brief overview of what a real vertiport would consist of by analyzing a theoretical model of one of the main manufacturers and researchers of VTOL aircraft [19] and two reference aircraft will be defined to better visualize the magnitude of the challenge. Then, the best approach for the integration of this type of operations will be defined, through the use of existing airport infrastructure or through the installation of new vertiports depending on the nature of the operations and the design of the vehicles and, finally, the necessary resources will be assessed so that the UAM can be implemented safely and efficiently.

6.1. Vertiports design

In order to get a general idea of what the necessary infrastructure to implement in conventional airports for the integration of UAM operations consists of and to define a final solution, throughout this section the vertiport model proposed by the aerial mobility company Lilium is established as a reference (see Figure 6.1).

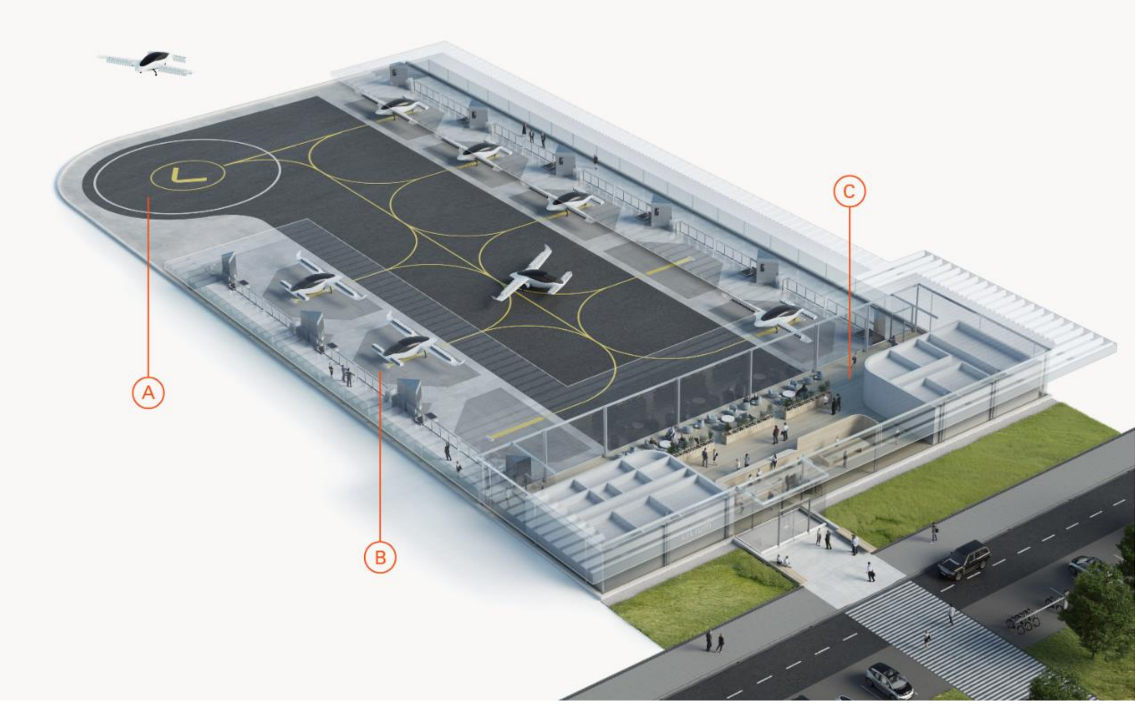


Figure 6.1. Model of a theoretical vertiport designed by Lilium [19].

It is important to mention here that the model that can be seen in Figure 6.1 is just a model that represents, in an isolated way, the three different areas in which a vertiport to be built in the existing airports for the integration of the UAM would consist of and that does not take into account the rest of the airport environment components (conventional runways, navaids, control tower, etc.). These three zones are, depending on each letter that refers to them in the figure:

A. Takeoff/landing area. It is based on the current heliports design (Annex 14, ICAO, Vol. II), where the specific take-off and landing areas called FATO (Final Approach and Take-Off) or TLOF (Touchdown and Lift-OFF) are considered and surrounded by a security zone. On the ground, the VTOL vehicles will move by means of their wheel trains along the defined taxiways to and from the parking stands.
B. Parking area. Passengers will embark and disembark from the VTOL vehicles through the boarding areas with their respective loads. These zones will be designed to ensure there is no danger to passengers or crew as they move around the aircraft while maximizing the efficiency of the vertiport. In addition, in these positions the cleaning, loading and inspection of the vehicle will be carried out before its next trip.
C. Terminal building. In this case, and instead of the additional and specific terminal proposed by Lilium for the flow of UAM passengers, it is considered that the best option to reduce both the impact of the UAM and the economic investment in infrastructure is to consider the existing terminals and connect them with the areas described above in order to also achieve a more efficient use of the available space. The terminal-shunting area passenger connection must be as agile and fast as possible in order to avoid passenger congestion and delays.

6.2. Reference VTOLs

The next step to analyze the necessary infrastructure to accommodate VTOL vehicles in airport environments is to choose a reference aircraft that, theoretically, will operate in each of the airports where UAM operations will be implemented. This, obviously, does not mean that the same type of aircraft will always operate at all airports, however, it is a good way to limit the challenge and reach a final solution. This choice will notably mark the design of the vertiport or the necessary infrastructure to be installed, since it will determine the dimensions of the most important area for UAM operations to be carried out, the takeoff/landing area or TOLA.

In choosing the reference VTOL, the findings previously found in section 3 about the different designs and configurations of VTOL vehicles found in the literature should be taken into account. In this section, to simplify this selection and avoid delving into each subgroup, the most general classification of these aircraft is considered, that is, Rotary-Wing Cruise aircraft and Fixed-Wing Cruise aircraft.

It is therefore that, instead of one, two reference aircraft will be selected in this study in order to, in a general way, cover all the VTOL vehicle designs found nowadays.

Given not only the advanced stage of development in which they are, but also the large amount of information on the specific characteristics (manufacturers' manuals, main dimensions, etc.) that can be found in the literature, the two reference models chosen to carry out this study are the VoloCity and the Lilium JET designed by the German air mobility companies Volocopter and Lilium, respectively.

6.2.1. VoloCity by Volocopter

The VoloCity is an electric VTOL (eVTOL) model designed by the Volocopter company (pioneer since 2011 in the design of these types of vehicles). The VoloCity, belonging to the Rotary-Wing Cruise aircraft group, has 18 rotors driven entirely electrically by 9 batteries and has a capacity for 2 passengers in total, including their respective hand luggage (see Figure 6.2). This aircraft can fly at a speed of 100km/h and has a range of 35km [20]. Other interesting specific features for this study taken from the manufacturer's manual are provided in Table 6.1.

Table 6.1. General specs of VoloCity by Volocopter extracted from the manufacturer's manual [21].

	Max. Take-Off Mass (MTOM)	Max. Payload	Operating empty weight (OEW)
Declared masses	900 kg	200 kg	700 kg
	Overall height	Diameter of the rotor incl./excl. rotor	Diameter of a single rotor
Declared dimensions	2.5 m	11.3 m/9.3 m	2.3 m

The VoloCity model is developed to meet each and every one of the standards and requirements established by the European Aviation Safety Agency (EASA) and already complies with multiple operational certifications. This model has already performed flight demonstrations in Germany, Dubai, Singapore and Helsinki and commercial flights are expected to be launched in Paris and Singapore by 2024.

Figure 6.2. VoloCity by Volocopter real model [22].

6.2.2. Lilium JET by Lilium

The Lilium JET is also an eVTOL model designed by the Lilium company, a leader and pioneer in the UAM sector too. This model, which is currently in the 5th generation of this type of JET, belongs to the Fixed-Wing Cruise aircraft family and is powered by 36 electric motors (see Figure 6.3). Its versatile design makes it have a capacity for 7 seats (1 pilot and 6 passengers). The Lilium JET can fly at a speed of 280 km/h and reach ranges of more than 250 km including reserves. As for the specific characteristics, according to the manufacturer, the Lilium JET has a wingspan of 13.9 m (45.6 ft), a length of 8.5 m (27.9 ft) and a Maximum Take-Off Mass (MTOM) of 3,175 kg [23]. Regarding the payload, to date, the Lilium company has not yet published the amount of luggage that the passengers will be able to carry onboard for the 7-seat model, as it is still in a testing phase. However, for the 2-seat JET configuration, the payload is 200 kg, therefore it can be assumed that each passenger will be able to travel with their respective hand luggage [24].

The main feature of the Lilium JET lies in its propulsion system, as it has smaller engines than those of other manufacturers, it is more efficient in horizontal flight, which translates into greater autonomy (although the efficiency in stationary flight, that is, in vertical takeoff and landing, is smaller). As of today, the Lilium JET is at a very advanced stage, having successfully completed multiple test flights and is about to achieve certification from both the EASA and the FAA.

Figure 6.3. Lilium JET by Lilium main dimensions (scheme done by own elaboration based on [25]).

6.3. Addressing infrastructure for operating schemes

Put in the context and the magnitude of the challenge, having analyzed the two different reference aircraft that will represent the integration of all the existing VTOL vehicle models in the airport environment and the necessary resources so that these vehicles can operate correctly, the next step to be carried out in this study is to identify the airport infrastructure to be implemented, taking into account various aspects such as the needs of the aircraft, the facilities already existing in conventional airports and the operational models analyzed in the previous section.

Starting from the definition of TakeOff and Landing Area (TOLA), which is any suitable place for takeoff and landing for VTOL vehicles both inside and outside an aerodrome [26], an important aspect must be addressed for the integration of this type of vehicles in airports. It is that, depending on their configuration and performance, the best way to integrate them (in terms of efficiency and safety of operations) will be either through the use and adaptation of existing infrastructure resources, or through the construction of new vertiports located further away from the conventional areas of operations. In other words, depending on the aircraft, the TOLA, which is the most important structural element for a VTOL vehicle to operate correctly, will be located either within what would be the area of operations of the airport in question, taking advantage of existing resources (such as for example de-icing areas, platforms, taxiways, etc.), or in areas further away from it with the disadvantage of having to install all the corresponding infrastructure.

Based on this premise, it is concluded that, due to their behavior similar to that of STOL aircraft and other small conventional aircraft, the vehicles belonging to the family of Fixed-Wing Cruise aircraft (represented in this study by the aircraft of reference: Lilium JET) will use the existing infrastructure in conventional airports, while, due to their performance rather similar to that of the helicopters that operate nowadays (even, as seen above, in some airports), the vehicles belonging to the group of Rotary-Wing Cruise aircraft (and represented in this study by the other reference aircraft, the VoloCity) will operate in vertiports installed in the vicinity of an existing airport, or inside an existing airport in areas further away from the conventional operations area.

Next, two hypothetical scenarios are presented below: the case in which Fixed-Wing Cruise aircraft will take advantage of the existing infrastructure to carry out their operations and another case in which it will be necessary to implement new infrastructure to accommodate the Rotary-Wing Cruise concepts. Each scenario will include certain operational schemes previously analyzed depending on their viability applied to reality and the necessary airport facilities and services will be evaluated in each case to accommodate, depending on each configuration, these vehicles in the airport environment.

6.3.1. Schemes involving existing infrastructure

As previously mentioned, the Fixed-Wing Cruise aircraft type vehicles will use the already existing facilities and resources (or adapted to their use) in the airport environment where they would be integrated, due to their design and performance similar to those of conventional aircraft. For this, three of the operational schemes previously analyzed in the previous section are considered: mixed use, closely spaced and converging/diverging operational schemes that will determine the necessary infrastructure and procedures for the integration of UAM services.

In order to analyze the behavior of future VTOL vehicles that would use the existing infrastructure at the airports where they are going to operate, it is of great interest to take current general aviation (GA) as a starting point. General aviation operations that, to get an idea of the operations framework that they cover, are, for example, pilot training flights, business aviation, civil research and rescue, recreational flights (gliders) - that is, all those operations that leave the purely commercial world, normally take place at aerodromes dedicated to each activity in question. However, as mentioned in the previous section (subsection 5.1 on the UAM background and current trends), it is not unusual to find general aviation at some conventional airports. In the latter, general aviation flights are managed with conventional operations using the same facilities and runways for their movement, with the difference of, once on the ground, general aviation is accommodated (in the majority cases) in what would be remote terminals, far away from commercial terminals. Note that, in some airports, there are reserved parking positions for general aviation aircraft next to the terminal building, but the normal case is finding them as mentioned, separately from the conventional platforms and gates.

Fixed-Wing Cruise aircraft configurations will follow a similar dynamic to that of general aviation at airports. They will use the same runways, procedures and facilities for both takeoff and landing as commercial aviation, taxiways for travel to/from the runways, etc. with the main difference with respect to the GA that, instead of being accommodated in remote terminals, UAM flights will be directed to the main terminal gates. This is due to the fact that the vast majority of VTOL concepts (and, in particular, the Lilium JET and VoloCity reference aircraft) are fully electric, so they require charging stations or battery exchange for their operation. Therefore, these stations must be located in a place close to the main power supply of the airports, that is, the terminal building.

Regarding the rest of the airport infrastructure that, like commercial aircraft, these vehicles will need to be able to carry out their operations in a safe and efficient manner, Table 6.2. briefly collects a series of services with their corresponding description of their functions to accommodate the new VTOL aircraft.

Table 6.2. General description of airport services necessary to accommodate VTOL vehicles using existing facilities [own elaboration].

Airport services	Description
Handling services	As seen in section 6.2. these aircraft and, specifically, the reference models, do not have the capability to carry heavy loads (passengers can typically bring only one bag) so it is not necessary to use any handling service.
Fueling (feeding stations)	As previously mentioned, most of these configurations are totally electric, therefore, although they will use the existing infrastructure at the airports, it is obvious that they will need power stations for recharging batteries that must be located close to the airports terminal buildings.
Platforms and parking stalls	The dimensions of the aprons and aircraft parking stands depend on the reference code of each airport. In this study, it is assumed that the airports where UAM operations will be integrated will have the necessary category to accommodate VTOL vehicles, therefore, they will use the same platforms as commercial aircraft (in addition, the Lilium JET wingspan is 13.9 m, far below from the smallest conventional aircraft).
De-icing areas	VTOL vehicles will use the same de-icing-anti-icing platforms as commercial aircraft, always trying, according to Annex 14 of the ICAO, not to interrupt or congest airport traffic. As in the case of the platforms, these areas have the necessary size and capacity to accommodate several commercial aircraft at the same time, therefore they will also be capable of servicing VTOL configurations in conjunction with other similar or even larger aircraft.
Passenger management	For boarding/disembarking passengers, the use of air bridges is not necessary since VTOL vehicles do not have sufficient height for the use of these devices to be optimal, so passengers will board and disembark from the aircraft parking place itself on the ground. Regarding the passengers’ flow transportation to/from the terminal building, passengers may travel on foot, as long as proximity and protection from other vehicles allow it, or through bus services or shared cars that, nowadays, are already implemented at most airports.

6.3.2. Schemes involving new infrastructure or vertiports

Today, we can find helicopters operating at some airports, especially in the United States, where the great distances that separate them from both the main metropolitan areas and residential neighborhoods make transfers to/from airports via helicopter really efficient in addition to the air congestion in this country, which being much less than that which occurs in the European countries, allows these operations to also be carried out safely.

Generally, the heliports that are under the jurisdiction of a commercial airport are located either in the vicinity of the airport itself or at a reasonable distance (which is usually large) from the runways and commercial procedures so as not to interfere with the rest of the aircraft. Going back to section 5.1 where it was talked about helicopter operations and general aviation flights at some of the major airports in the United States, we can once again look at the heat map of helicopter operations over a whole year in Figure 5.1, and if we look at the airports in SFO and LAX we can confirm that these operations are effectively carried out separately from commercial traffic in areas potentially far from the normal areas of airport operations. This is so, due to the characteristics of helicopters that differ greatly from those of conventional aircraft. In addition, for a heliport to be considered as such, it must comply, according to Annex 14 of the ICAO, Volume II, with a series of fundamental requirements since, apart from what would be the Final Approach and TakeOff Area (FATO, which for VTOL vehicles is the TOLA), it must have a wide security area to protect not only the operations of the helicopters but, in case of being located in the vicinity of an airport, to also protect the rest of the operations that are carried out in the airport environment. All this without having into account the necessary infrastructure for the treatment of passengers, luggage, so it is obvious that a heliport requires a lot of space around it and infrastructure to be implemented.

Due to their design characteristics and their performance, it can be considered that the Rotary-Wing Cruise aircraft configurations have a very similar nature to that of the helicopters that operate nowadays, so, according to what has been analyzed, they will follow the widely spaced and independent operations operational schemes further away from the conventional area of operations than the other operational schemes and therefore will require new facilities for their integration into the airport environment.

In operational terms, the Rotary-Wing Cruise aircraft will behave in a similar way to the current cases of helicopters at airports such as SFO or LAX: flights will arrive/depart from TOLAs located at a considerable distance from the runways and conventional operations areas so as not to interfere with commercial aviation and, once there, depending on the case, the connections with the terminal building will be made, as analyzed in the previous section, through air taxiing or transfers by land vehicles (see Table 6.2 on the necessary services and facilities to accommodate this type of configuration in the airport framework).

Table 6.3. General description of airport services necessary to accommodate VTOL vehicles using new facilities or vertiports [own elaboration].

Airport services	Description
Handling services	As for the existing infrastructure scenario, these vehicles do not have the capability to carry heavy loads so in this case it is not necessary either to use any handling service.
Fueling (feeding stations)	As mentioned in the previous section, most VTOL configurations are powered by fully electric systems, therefore, in this case, the implementation of new recharging/battery changing stations will also be required to supply energy to these aircraft.
ATC controllers	An additional air traffic controller is strictly necessary for the cases of independent operations and IFR arrivals in widely spaced operations, therefore, to cover the entire range of possibilities and ensure the safety and efficiency of operations, it is considered that to specifically manage this VTOL configuration flights is required an additional ATC controller.
Platforms and parking stalls	Unlike the previous case, these vertiports, being separated from the existing airport infrastructure, must include new parking spaces and platforms where these vehicles can remain between trips. To this end, and since in this section the case of helicopters has been considered in operational terms due to their similarity to Rotary-Wing Cruise aircraft, this issue will be approached from the regulations referring to helicopters in Annex 14 of the ICAO, Volume II, where it is specified that the parking position for helicopters (which will be adopted in the case of Rotary-Wing Cruise aircraft) will be such that it can contain at least one circle with a maximum total diameter of 1.2*D of the design vehicle [27]. Therefore, for this case it must contain a circle of 1.2*11.3m = 13.56m. For the platform design, it must support the dynamic load derived from the design vehicle activity, that is, 2.5 times its MTOM [27], so considering once again the VoloCity as the reference vehicle, it must support a load of 2.5*900kg = 2,250kg.
Passenger management	Leveraging again on the heliports case and, as in the case of the use of existing infrastructure, it is not necessary to use air bridges for passenger boarding/disembarking, so passengers will access and leave the plane from the same vehicle parking stand. Regarding terminal connections, as analyzed in the previous section, there are two possible cases for the long-distance transfers: air taxiing and the land vehicle services already implemented today, being the transfer to the terminal access door via air taxiway much more efficient and faster, although in some cases its implementation would not be possible.

7. Conclusions

The objective of this study was to investigate and analyze the airport infrastructure necessary to accommodate VTOL aircraft in the context of UAM operations. However, the lack of data and technical information at the time of writing has forced the author to make several assumptions about the integration of this type of flights at airports and to propose hypothetical scenarios to, a priori, identify the main barriers and obstacles in this implementation. There is a possibility that the conclusions drawn may not apply to the same level as that presented, however, this thesis is also intended to be taken as a reference for future analysis and research.

Due to the enormous variety of designs and configurations that have come to light in recent years, driven in large part by a growing interest in urban mobility and autonomous and electric vehicles, these aircraft have been generally classified into two big groups, Fixed-Wing Cruise aircraft and Rotary-Wing Cruise aircraft. Based on the operations that are currently carried out in some airports in an unconventional manner, especially general aviation and helicopters, some initial conclusions can be obtained about the use of new or existing facilities. Fixed-wing Cruise aircraft have design and performance characteristics similar to aircraft operating under general aviation, since many are private jets or recreational flights and pilot training aircraft, so a first approach to ensure the efficiency and safety of these models at airports would be that they operate in a similar way, taking advantage of the existing infrastructure. Similarly, the Rotary-Wing Cruise aircraft, due to its clear similarity with the current helicopters, would need new infrastructure for its integration in the airport environment, since the current trend indicates that the helicopters operate in a segregated manner from the conventional traffic, in maneuvering areas far from the runways and conventional terminals. It is important to mention here that there are isolated cases such as the Valencia Airport example, in which large helicopters use the same runways as commercial aviation for their operations [28]; however, this study considers the general case. After this first approach, various airport facilities (handling services, fueling stations, platforms, etc.) were explored for both cases (use of new/existing infrastructure) with the aim of providing VTOL vehicles with the necessary services for the efficient integration of UAM operations in airport environments and based on this, the main conclusions of the thesis can be obtained.

First of all, it is interesting to reflect on the five operating schemes analyzed previously. As mentioned earlier, one of the main barriers in the integration of UAM operations at conventional airports is to maintain existing levels of efficiency without compromising airport operational safety while trying not to exceed the workload of air traffic controllers. However, at the planning level, many other factors are also important, such as the investment required to build new infrastructure necessary for new operations to be carried out, since economic viability is essential for this integration to really take place. Keeping in mind the descriptions previously made about each scheme, it can be concluded that there is a trade-off between the controller workload together with the investment in new infrastructure and the distance that separates the UAM operations from conventional traffic. The closer UAM operations are carried out to conventional operations, the lower the investment required from the airport infrastructure point of view, but the greater the workload of the controller(s) (because, in some cases, they will have to manage existing conventional operations together with new UAM operations) and, the further UAM operates from conventional traffic, the greater the necessary investment in infrastructure will be, in addition to complicating access to the terminal building.

As far as financial aspects are concerned, a first essential investment for the implementation of UAM operations is the construction of new recharging or battery change stations, since, as has been seen throughout this thesis, the vast majority of vehicles VTOL are fully electric. This, in turn, implies an additional economic cost for the case in which these operations are carried out far from the conventional area of operations, since the main power supply of the airport is in the terminal building, therefore, it would be necessary to carry the electrical current from the terminals to the locations where this type of aircraft would operate through long cables. From this aspect, the closer the UAM can operate to conventional flights, the better it will be from an economic point of view for the viability of implementing these operations, since it will be possible to take advantage of (or adapt depending on the situation) part of the existing infrastructure at the airports. As far as air traffic management is concerned, the controllers' workload saturation problem can be addressed, if it occurs, by opening new positions to manage conventional traffic together with UAM flights in an agile and flexible manner. On the other hand, for concepts that operate separately from conventional airport traffic, in areas further away from the runways and the terminal building, the construction of new infrastructure would be necessary to accommodate these operations with the economic implications that this entails.

As a final observation and, based on the research carried out throughout this thesis and the findings found, the following can be concluded: with the aim of reducing the operational and economic impact in the integration of UAM operations in airport environments, the most viable option would be a gradual implementation of the concepts found in the literature. In other words, integrate first the vehicles belonging to the Fixed-wing Cruise aircraft family that would operate in conventional maneuvering areas using the existing infrastructure and, if it works successfully and does not pose an obstacle to conventional aviation, study an expansion of these type of operations using more concepts such as Rotary-Wing Cruise aircraft and building new infrastructure and facilities in order to accommodate them.

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ANNEX

TITLE: Assessing the airport facilities in the context of UAM operations

TITULATION: Bachelor's degree in Aerospace Systems Engineering

AUTHOR: Álvaro Hernando López

DIRECTOR: Jovana Kuljanin

DATE: October 2022

Annex

In order to elaborate the general mission profile analyzed in section 4.2, the NASA RVLT project analyzed a series of locations throughout the United States with their respective characteristics (such as climate, geography, population distribution, etc.) with the objective of establishing a general location with general conditions that consider the main cities that would potentially integrate the UAM into their urban mobility network. This Annex includes the main research carried out by the NASA team to study this standard scenario on which the implementation of the general mission profile for the UAM is based.

Twenty-eight metropolitan areas belonging to the United States were selected for the studies of the missions with their respective requirements, mainly the most populated, with high volumes of existing commercial air traffic and problematic ground congestion, also ensuring a good geographic diversity and metropolitan areas that have large numbers of people who travel very long distances to get to work (mainly because they have to travel from the outskirts of such metropolitan areas to the center where their workplace is located). Such metropolitan areas are: Atlanta, GA; Boston, MA; Charlotte, NC; Chicago, IL; Cincinnati, OH; Dallas, TX; Denver, CO; Detroit, MI; Honolulu, HI; Houston, TX; Las Vegas, NV; Los Angeles, CA; Miami, FL; Minneapolis, MN; Nashville, TN; New York City, NY; Orlando, FL; Philadelphia, PA; Phoenix, AZ; Pittsburgh, PA; Portland, OR; Salt Lake City, UT; San Antonio, TX; San Diego, CA; San Francisco, CA; Seattle, WA; St Louis, MO; and Washington, DC [15].

The first aspect to take into account when modeling a VTOL vehicle flight, as in the world of commercial aviation and large-scale flights, is the weather. The weather characteristics of the cities mentioned above will largely drive some of the requirements for the vehicles that will operate there along with the general profile of the missions that they will carry out. In its study, NASA primarily considered density altitude and winds in order to specify the altitude and wind conditions in which VTOL aircraft must be able to operate.

In order to determine the altitude above mean sea level (abbreviated as MSL) from which the VTOL vehicles will supposedly operate in the sizing missions, people from NASA compiled the meteorological data of the so-called Meteorological Terminal Aviation Routine (METAR) reported by the Iowa State University over 50 years (from February 26, 1968, to February 26, 2018). From the analysis of these data for the airports of each of the selected metropolitan areas, the density altitude for each of them can be calculated and, analyzing the historical trends, an adequate elevation for both takeoff and landing is determined. Density altitude calculation was calculated as follows [15]:

- Data from METAR provides the altimeter setting based on local atmospheric conditions. This altimeter setting is converted to barometric pressure (p) at the airport based on a 1976 standard atmosphere assumption.

- In order to calculate the saturation pressure of water (p_s in Pascals) at the local dewpoint (t_d where t_d is expressed in degrees Celsius), the Tetëns' formula ($p_s = (610.78)10^{(7.5t_d)/(237.3+t_d)}$) was used.
- The partial vapor pressure of water present (p_v) was calculated from the saturation pressure (p_s) and the relative humidity ($RH\ as\ p_v = p_s RH$ in Pascals).
- The partial pressure of air (p_a) was obtained from the local barometric pressure (p) and the partial pressure of water (as $p_a = p - p_v$).
- Density (ρ) was found from the temperature and partial pressures as $\rho = \frac{p_a}{RT} + \frac{p_v}{R_v T}$ where R is the air gas constant (287 J/kg-K), T is the local temperature (in Kelvin), and R_v is the water vapor gas constant (461.5 J/kg-K).
- The standard atmosphere was used to convert density to density altitude.

Figure A.1 shows the Cumulative Distribution Function (CDF) for density altitude at each of the twenty-eight airports, and Figure A.2 shows a more detailed comparison of density altitude data for each of them.

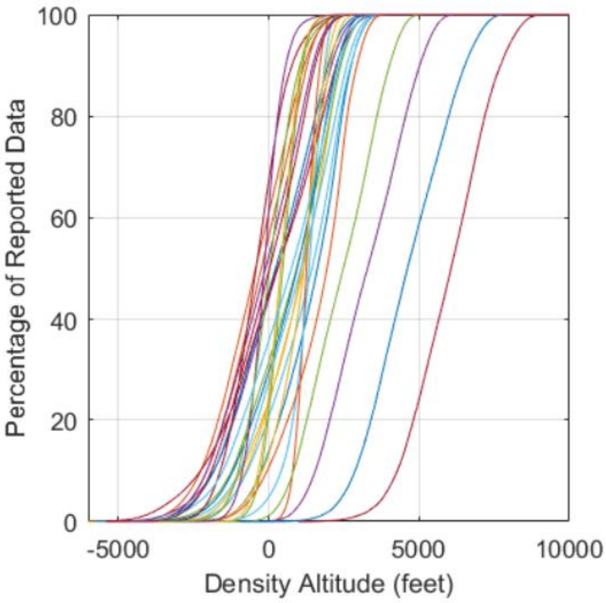


Figure A.1. Cumulative distribution Function (CFD) of Density Altitude (in feet) for the 28 metropolitan areas selected by NASA [15].

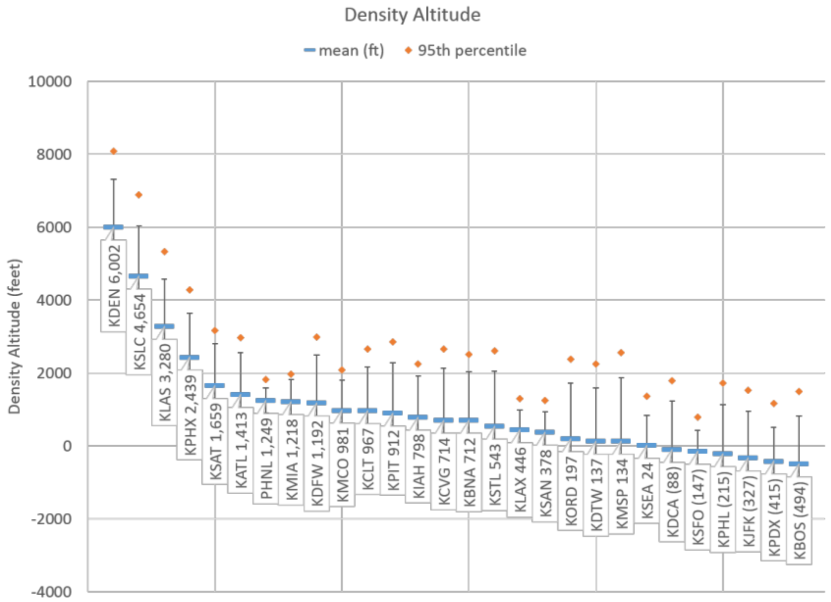


Figure A.2. Density altitude (in feet) for all 28 cities selected by NASA [15].

As we can see in Figure A.1, with the exception of Denver (represented by a magenta curve), Salt Lake City (shown in blue), Las Vegas (shown in purple) and Phoenix (shown in green) that present the highest density altitudes, the rest of the locations have lower density altitudes and much less variation between them so, based on the data obtained, NASA proposes a takeoff and landing altitude requirement of 6000 ft MSL for vehicle design missions. With this selection, a VTOL aircraft can operate on a normal day in all locations and on the 99th percentile day in all cities except Denver and Salt Lake City.

In addition, comment that if operations want to be carried out throughout the year in Denver and Salt Lake City, they would have to be restricted by a reduction in the payload or range capacity apart from the already defined altitude requirement.

In order to model wind conditions in which the VTOL vehicle missions can be carried out while ensuring the safety of operations at all time, NASA also analyzes the data on wind speeds and wind gusts for the 28 cities extracted once more from the METARs. Figure A.3 shows the CDF of the wind speeds for these cities' graphical representation and a more detailed comparison of the wind speeds for each of them can be seen in Figure A.4.

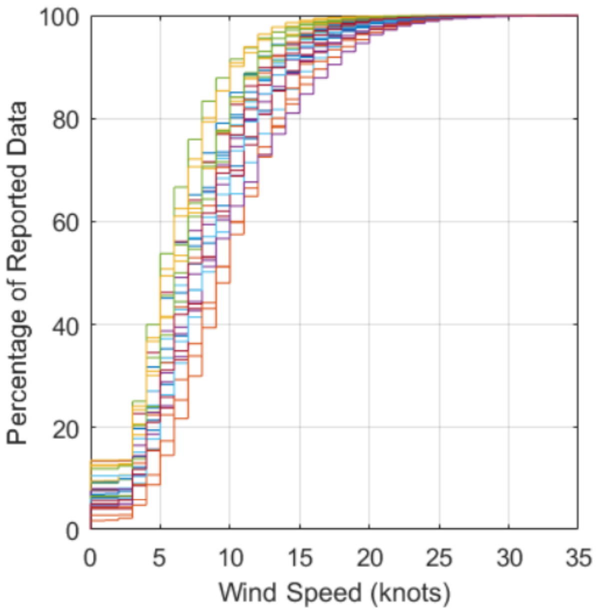


Figure A.3. Cumulative distribution Function (CFD) of Wind Speed (in knots) for the 28 metropolitan areas selected by NASA [15].

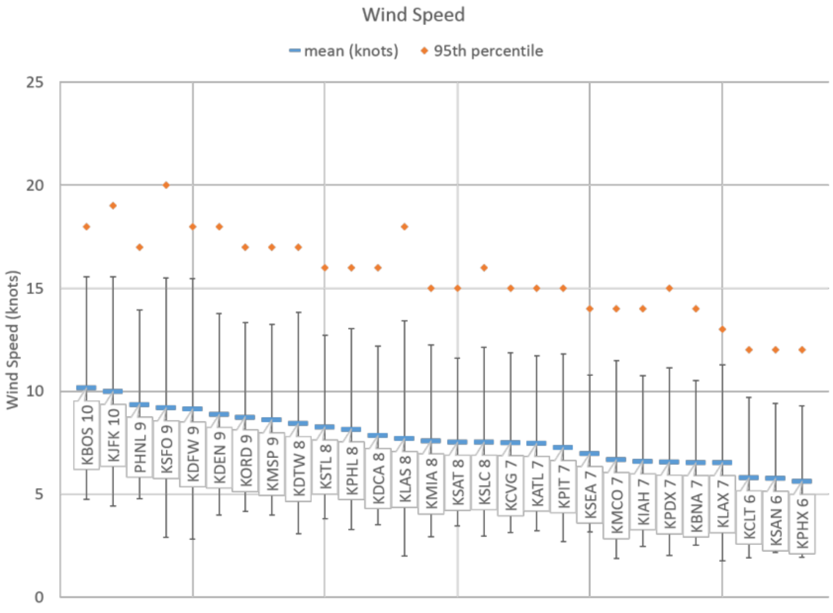


Figure A.4. Wind speed (in knots) for all 28 cities selected by NASA [15].

Based on these data, it was concluded that an aircraft capable of maintaining six degrees of freedom control in a sustained wind of 20 knots would be able to operate in any of the 28 cities a minimum of 95% of the time. However, for the sizing mission, NASA proposes a 10-knot headwind requirement, which ensures that the aircraft can operate at least 50% of the time. The reason why a higher headwind requirement is not necessary is that, apart from the fact that not all flights will be directly oriented into a headwind, the reservation requirements will take into account some of the uncertainty in wind speeds, just as is done in the commercial aviation [15].

To finish modeling the meteorological conditions to which the aircraft will be subjected in the missions proposed by NASA, two graphs were generated again to model possible wind gusts that could affect the VTOL vehicles, the one in Figure A.5 that shows the CDF of the wind gusts for the 28 cities and that of Figure A.6 where, again, a comparison of the wind gusts for these cities is represented.

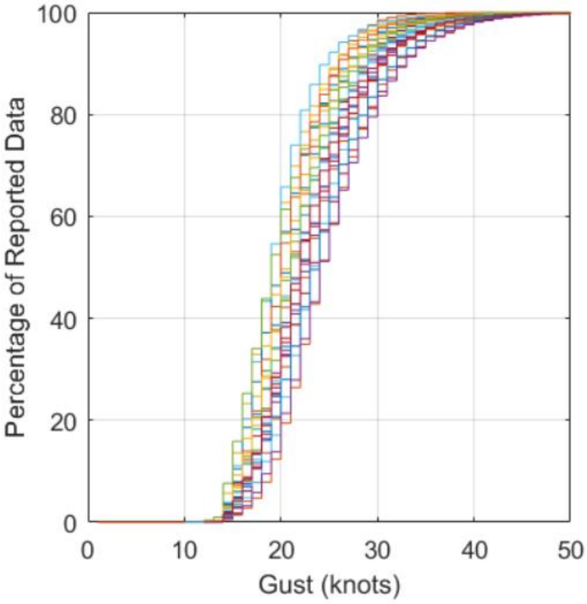


Figure A.5. Cumulative distribution Function (CFD) of Wind Gust (in knots) for the 28 metropolitan areas selected by NASA [15].

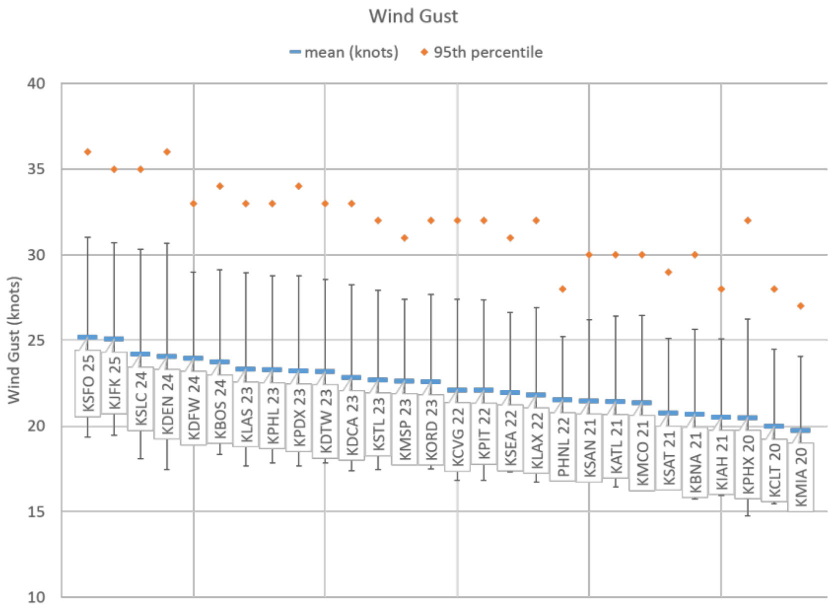


Figure A.6. Wind gust (in knots) for all 28 cities selected by NASA [15].

Based on these wind gust data, an aircraft capable of maintaining stable control in wind gusts up to 35 knots could operate 95% of the time in all but two cities: Denver and San Francisco whose 95th percentile it is slightly higher. However, NASA proposes this wind gust requirement of up to 35 knots for its sizing missions [15]. (As it was mentioned before, the reserves take into account all kinds of contingencies that wind can cause).

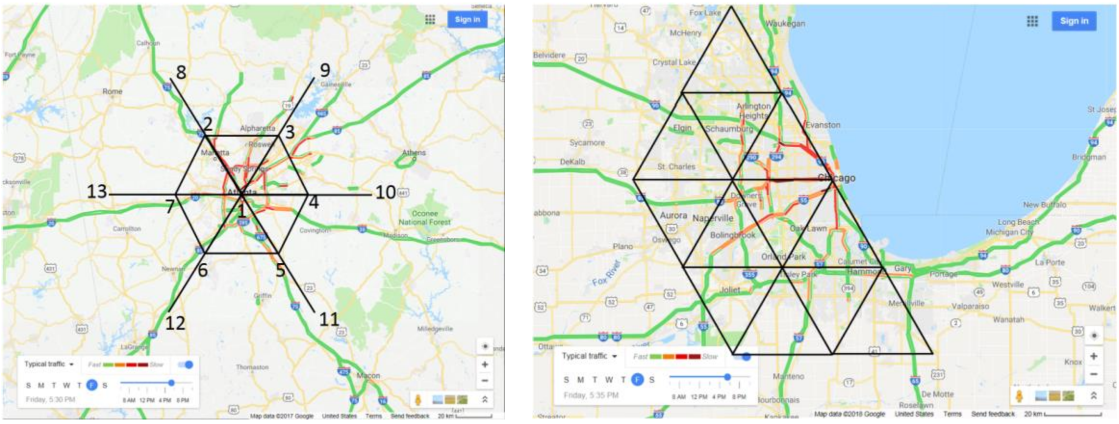
Once the meteorological conditions in which the operations are going to be carried out in the proposed missions are taken into account, the second aspect to consider is a generic representation that roughly models the set of 28 cities chosen for the project study. A generic representation of vertiport locations is useful for modeling UAM networks and identifying the nature of a sizing mission, including reservation requirements.

The generic city model chosen by NASA comes from observing many of the 28 cities of interest whose configuration of highways and other land transport routes consist of a "wheel-and-spoke". This configuration consists of a series of interstate highways radiating from city centers towards surrounding smaller communities while one or more concentric beltways connect the smaller communities to one another, thus providing alternative routes to bypass traffic. Most cities have one beltway that surrounds the city center and between four and eight main spokes that connect the urban core with smaller communities [15].

Taking this into account, the generic model of vertiport placement proposed by NASA to achieve similar mobility around the city consists in a hexagon with a seventh vertiport in the center of the city, thus forming six equilateral triangles. In case larger areas need to be covered, this model can be extended by placing additional equilateral triangles or even individual vertiports around the inner hexagon, depending on the case. The advantages offered by this model are that a large part of the metropolitan area of the cities will be connected in a similar way to its current road system and its simplicity due to the fact that the distance from any vertiport to the next closest one is always the same [15].

This hexagonal model will be used in conjunction with population distribution analysis to determine the length “L” of each side of the equilateral triangle. In Figure A.7 a), we can see an example of this generic hexagonal model superimposed on the Atlanta metropolitan area, where the distance of L (i.e. each side of the triangles) is 18.75 nmi. Using this simple model, we see that most of the Atlanta metropolitan area can be connected through vertiports.

However, the disadvantage of this generic hexagonal model is that it does not capture all metropolitan areas equally in an ideal way. In cities like San Francisco, Boston, Miami, and Salt Lake City that are located in an environment where there are multiple geographic constraints, such as mountains or large bodies of water (lakes, sea, etc.), the full hexagonal generic city model is not the appropriate one. Nevertheless, in many of these areas, this model can be adapted by applying a modified hexagonal model in which certain vertiports are removed to provide a reasonable representation of the area as we can see in Figure A.7 b), where an example of this modified generic model is shown applied to the city of Chicago whose geographic restriction is Lake Michigan.



a) Full hexagonal model applied to the city of Atlanta.

b) Partial second-order hexagonal model Applied to the city of Chicago.

Figure A.7. Generic hexagonal model applied in two different cases: one in the city of Atlanta without geographical constraints and another modified to better adjust to the geographical conditions of the city of Chicago [15].