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Assessing potential urban air mobility traffic density in a metropolitan area like Chicago

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Driving in metropolitan areas means hours of traffic jams, which results in a reduction of productivity for both the city and people's lives. Therefore, urban air mobility/air taxis are proposed as a solution to this overwhelming problem. As a consequence, this study is focused on determining the number of feasible trips that could fly over an urban area (in this study, the City of Chicago) considering passenger costs for the air taxi trip using short-, medium-, and long-term operating cost models suggested by Uber. To estimate the number of trips, the study starts with historical data recording the number of commutes in the city together with the origin and destination coordinates for these commute trips. The distribution of these commutes over one day estimates the number of trips at a given hour of the day. The Open Trip Planner API calculates the duration of these commutes, which allows calculation of the effective cost of the trip when using an air taxi for part of the trip. The computational model for this study compares the effective cost of a trip using the air taxi, for part of all the trip, to the effective costs of using only ground-based public transit or a passenger-owned automobile for the same trip. Trips where effective cost is lowest when using air taxi provide a count of the number of UAM trips conducted over the city. Following this initial estimate of the urban airspace density, the model can subsequently assess the impact of additional considerations about restricted areas of the city (in Chicago, the class B airspace for Midway Airport, is one example). Thereby, a first approach of feasible routes is implemented using an optimization path algorithm.

I. Introduction

Nowadays, we are facing an increasing number of vehicles in urban areas, which results in a longer time to travel from one point to another within these cities, as a consequence of huge traffic jams. Besides, pollution is becoming a relevant problem when thinking about the future of the planet, especially when people think of global warming. In this case, the internal combustion of fossil fuel is the main source of pollution since this chemical process originates gases that vehicles deliver to the atmosphere.

In many cities, alternatives to these traditional ways of transportation are appearing. Not only companies like Uber or Lyft are trying to promote the use of ridesharing, but many others are introducing scooters, motorbikes or even shared cars as a different approach to owning a vehicle. Their main objective here consists of decreasing the congestion and pollution in cities. Moreover, recent advances in batteries and electric systems are allowing many of these companies to introduce electric vehicles to reduce further pollution in urban areas.

Besides, many governmental organizations like the National Aeronautics and Space Administration (NASA), the Federal Aviation Administration (FAA) or even the European Union are performing research related to a new mode of transportation that could be applied in cities within the near future. Urban Air Mobility (UAM) is expected to be a partial solution to the problems of congestion delay and transportation-related pollution, which are arising in very populated cities. Most of the proposed UAM aircraft will be electric Take-Off and Landing (eVTOL) vehicles, which will allow reducing traffic, as well as pollution.

However, many challenges appear when thinking of this new kind of vehicle; for example, determining the appropriate range, passenger capacity, flight speed, separation from other vehicles and structures, etc. Thereby, what these organizations are trying to accomplish with their studies is to define all these characteristics and parameters, so that this new service can be smoothly introduced without any mishap.

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This paper considers the trips that people usually perform on a typical day within an urban area, in this case, the city of Chicago, so that we can define trends in the commutes. Our study will use information provided by the city of Chicago, as well as other sources like the US census or the Chicago Transit Authority (CTA). Once this information was acquired, a computational framework was created using Matlab and the Open Trip Planner Application Programming Interface (API) to compute the duration and distance of the trips. To achieve this goal, some information regarding the characteristics of these vehicles will be necessary; this paper uses information from Uber Elevate.

This work also implements an optimization problem to define feasible air routes between places where the UAM aircraft can land and takeoff (for simplicity, this work calls these "UAMstops"), taking into account the presence of geographic limitations like buildings or restricted airspace. The inclusion of the mission profile, together with a more realistic flight path, is also relevant in the determination of these trips, because these issues do have a noticeable impact on the the flight time.

A. Literature review

As mentioned before, Urban Air Mobility is getting more relevance among the aeronautics field due to the improvements and new technologies introduced recently that make this service considerably more feasible than it was before. However, NASA was a pioneer in this concept, performing studies like [1] in 1972, about some operational and economic characteristics of what we now call UAM. Nowadays, Uber is among numerous companies putting a huge effort in this futuristic mode of transportation, since they recently published Refs. [2, 3], in which they state some requirements and instructions for the implementation of UAM. They collect in these documentation many results previously stated by NASA and other organisms. Due to the level of detail and the extensive coverage of the Uber publications, this information has been one of the main sources for this study.

Roy et al. [4, 5] expose in their research a first approach of what has been used in our study. They made a comparison between various modes of transportation in a similar region: the midwest area. However, unlike our study, they focused on door-to-door regional trips, instead of urban trips, with both a generic and a specific trip approach. Whereas their first study [4] mainly studies conventional take-off and landing and electric conventional take-off and landing aircraft. Their second study [5] extends their framework by including VTOL and eVTOL aircraft. Our work here also implements the effective cost metric. This effective cost definition was firstly introduced by Mane and Crossley in [6], where they also studied factors - like the selection of the aircraft - that influence the feasibility of implementing longer range, on-demand air taxi service.The effective cost metric incorporates the concept of value of travel time, which others, like Gawadiak et al. [7] also use in similar studies.

Studies about UAM have been done in many regions of the United States, but the San Francisco Bay area is one of the most used due to its exceptional characteristics, like the number of long trip commuters, the high income of the population or the weather conditions. German et al. [8] envision eVTOL for transporting cargo instead of passenger in the research they performed in the Bay area. Their idea of discretizising the city using the US government definition of blocks and tracts was useful for the development of our study, as well as their centroids approach. The city population and their mean income was a relevant metric for their study to allocate the UAMstops. Although they do not consider the airspace for flight path planning, they do use it to place the UAMstops through an optimization algorithm. Additionally, Antcliff et al. [9] expose in their study an average reduction of 20% for urban trips and of 30% for the suburban in the area of Silicon Valley. However, this study is more focused on the infrastructure and the path that these aircraft should follow. They propose overflying public roadways, as well as a minimum altitude of 500 feet over private properties. They also conclude that noise is one of the most important aspects to consider and propose distributed electric propulsion as a solution.

The study of NASA performed by Mueller, Kopardekar and Goodrich [10] is also a relevant reference, because they study the behavior and requirements of a high-density airspace, such as, the necessary infrastructure or the avoidance of existing and traditional airspace. In their study, they propose to equip On-Demand Mobility (ODM) aircraft with advanced technologies; i.e., algorithms or sensors so that these aircraft do not need the implication of traditional air traffic control. Another important fact of Ref. [10] is the estimation of 1,200 aircraft operating simultaneously in a large metropolitan area, which produces a density of around 1 aircraft/nmi^2, compared to the traditional density of 1 aircraft/(250-500)nmi^2. In their study, they use a value of 4 trips/hour over 16h of operations in a day, with 2 passengers per trip, which results in a total of 150,000 passengers per day. In this case, they also take into account the existence of restricted B and C airspace, as we have done in our research, and they show the current corridors for VFR over these areas as well.

This predicted increase in the number of aircraft has motivated the development of the future next-generation air traffic control which, as it is commented by Erzberger et al. [11], can help to introduce UAM. Guerreiro et al. [12], as part of a NASA study, have developed a mission planner algorithm for ODM. To achieve this mission planning, they use constrained 4-D trajectories where they assume only 3 passengers in comparison to other studies. Similarly, Kohlman and Patterson [13] model the number of flying vehicles to meet demand, along with the number of operations in an UAMstop. However, unlike other studies, they do not consider the flight paths. Reference [13] does use 10 minutes of waiting time for other passengers which is similar to our assumption.

Looking at the current situation where no previous studies about the UAM in a specific city, specially a comparison between different options of commuting has been performed, this study will be focused on trying to define the number of air taxis that could exist in a city like Chicago while considering the option of other ground-based existing modes of transportation.

II. Region of study

To proceed with our Urban Air Mobility study, it is necessary to find information about the city of Chicago, like the population, its divisions, as well as the commutes that people usually make.

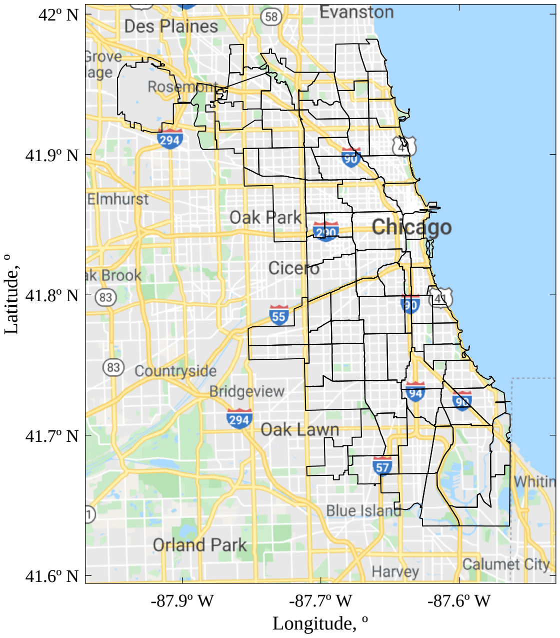

Fig. 1 City Community Areas

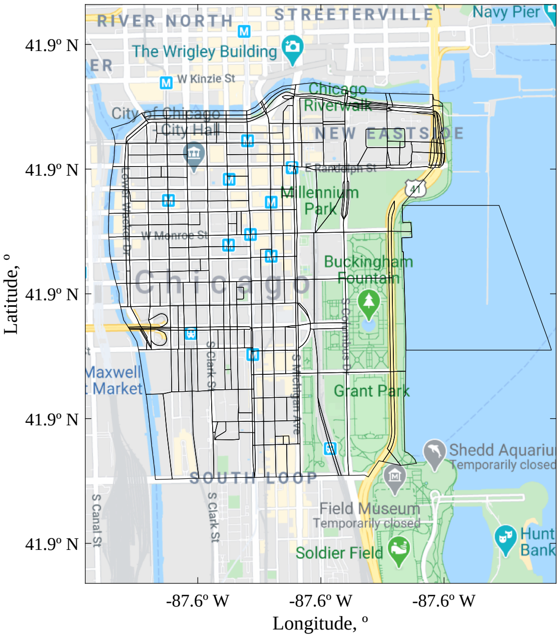

Fig. 2 City Community Blocks (Area 32)

The city of Chicago is divided into a total of 77 *community areas*, whose names and boundaries can be found in [14]. These areas are neighborhoods-like districts designated by some names and numbers. A representation of these areas is shown in Figure 1.

Another division applied to cities by the US census are *tracts*. As a consequence, each community area has a set of smaller partitions that can be obtained in [15]. The city of Chicago has a total of 866 tracts; this has remained practically constant since 1920. This kind of division is supposed to be homogeneous in terms of population. This tract division is the one that Ref. [8] used to perform the analysis of VTOLs for urban cargo.

Finally, the US census also creates another kind of division to discretize the city, known as *blocks* (Fig. 2). These blocks are eventually what may be identified in cities as a block of buildings. In this case, Chicago has around 10,000 blocks and due to its location accuracy and the existing amount of data, this was the selected discretization method.

A. Travel trends

The Chicago Metropolitan Agency for Planning (CMAP) publishes information regarding the amount of people that are commuting to work at a given moment of the day in the city of Chicago [16]. These travel trends show two peaks of traffic at around 7:30 AM and 5:30 PM, which usually correspond to the start hour of working or to the finish hour. In this study, we will only consider one way trips (from home to work), thus we are only influenced by the first peak.

Our modeling approach here uses the arrival time of commuters to their work location as the time parameter to identify trips. Thereby, these trips can be distributed along one day by using a probabilistic model.

The arrival time information is not provided by the US census [17] but, according to the information provided by CMAP [16], commutes in Chicago usually last around 31 minutes. However, the duration of the trip highly depends on the mode of transport, from a maximum of 65 minutes when using train to a minimum of 13 minutes when walking. Figure 4 shows the average travel time per mode.

Therefore, our approach uses the average time of the commutes (31 minutes) to shift the mean of the trips in progress distribution to the right, to estimate the arrival time probability distribution (Fig. 3).

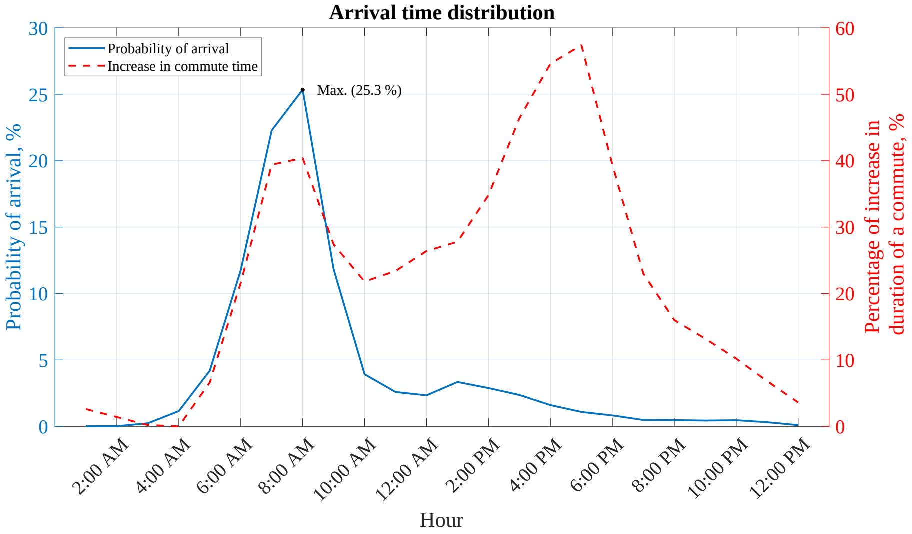

Fig. 3 Arrival time and increase in commute duration probability distributions over a 24-hour day

The travel trends from [16] not only indicate the probability of arriving at a given hour, but they also show the trends in the traffic density. The change in the traffic congestion at the typical rush hours result in an increase in the duration of a commute. Therefore, from the dataset [18] we have obtained the distribution of the increase in time depending on the hour; this also appears in Fig. 3 as the red curve.

Figure 3 shows one of the peaks previously mentioned in home-to-work arrival time, which coincides with one of the peaks of congestion. The second congestion peak is related to the typical afternoon rush hour. Again, this work is concentrating on the home-to-work trips, so the afternoon delay is applied to those afternoon home-to-work trips.

B. Population

As in [8], information regarding the population distribution is also relevant to define the location of the UAMstops and these data has been obtained from [19]. This allows the assignment of population to the corresponding block, which then let us determine the distribution of the population in a tract consisting of multiple blocks. This is extremely helpful to define the centroid of a given area in terms of population.

The blocks are the smallest geographic division of the city of Chicago that we have accessed for this work. We have population data for each block, and we assume that the entire population for each block is located at the geographic centroid of the block. This will be used for origins of the trips. To assist with subsequent placement of notional UAMstops, we will consider one stop per community area, so we also need the population-weighted centroid of each area. The K-means clustering algorithm provides the approach to determine the location of this population-weighted centroid. This uses an unsupervised machine learning approach to find K = 1 (for our study) centroids in a selected area given a set of variables that characterize the dataset. Here, we used the coordinates of the block geographic centroid and the population of the block. The Figure 5 shows the centroid for the downtown community area.

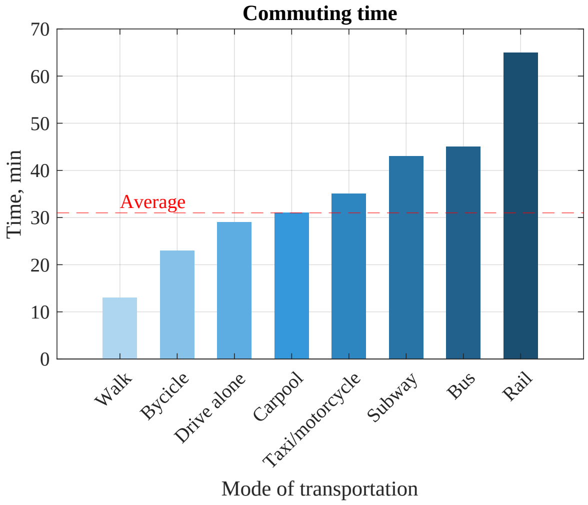

Fig. 4 Commute duration

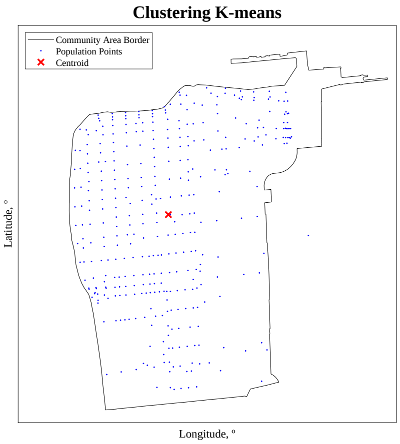

Fig. 5 Centroids in terms of population in downtown Chicago (Community Area 32,"Loop")

C. Income

A similar procedure has been followed for the income distribution. The mean income per tract is provided by [20] for 2018, and we have followed the same procedure as in [8] to estimate the income of each person residing in a tract. Using the regular amount of labor hours provided by the US government (2,087 hours/year), we further estimate the income per hour for each person in the city of Chicago. This data will be used to define the value of time for each citizen so that the effective cost can be calculated (this will be described below in section III.D).

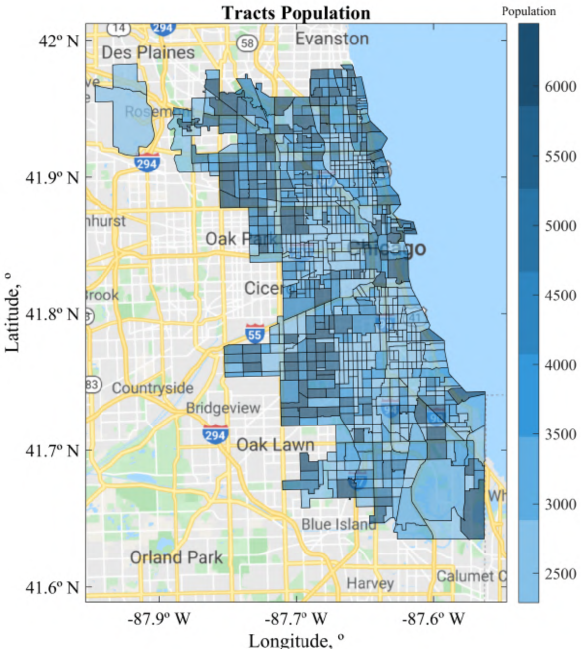

Fig. 6 Population distribution

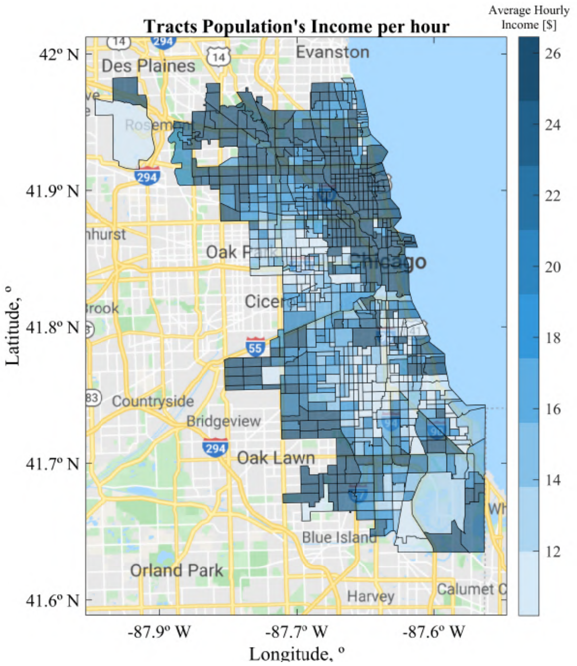

Fig. 7 Population income distribution

D. Commutes

The last important aspect that is necessary for this research is related to the home-to-work commutes occurring in Chicago on a normal day. The US census [17] states that in the city of Chicago there are approximately 740,075 commutes that have an origin and destination within the boundaries of the city. However, in order to decrease the computational cost of dealing with such a large number, some filters have been applied. According to [16], the average time that people require to commute when they walk in Chicago is around 13 minutes. Therefore, knowing that the average walking speed is about 3.1 miles/hour, the minimum distance used as a threshold would be 0.7 miles, so that a commute can be actually considered a commute. As a consequence, this study considers a total of 657,627 commutes because we are starting from a data set that considers trips with an origin and destination within the boundaries of the city, the work does not consider trips originating (or ending) in the surrounding suburbs.

Thanks to this data, information about the most typical origin destination areas of the city may be identified. Figure 8 shows some of the most common origins for the home-to-work commutes. The Loop (area 32), Near North Side (area 8), Near West Side (area 28), West Town (area 24), and Lake View (area 6) are some of the main destination examples shown in Fig. 9.

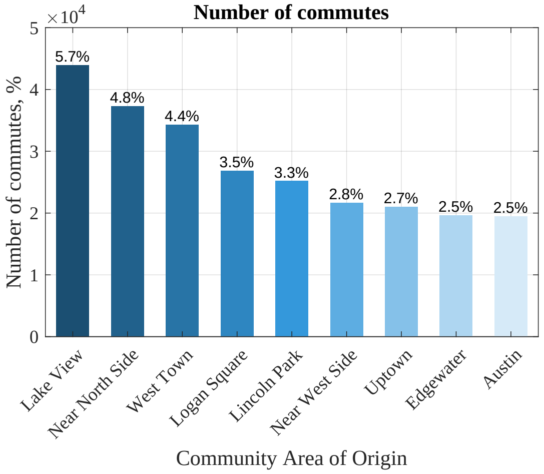

Fig. 8 Origin areas which represent the 30% of the total commutes

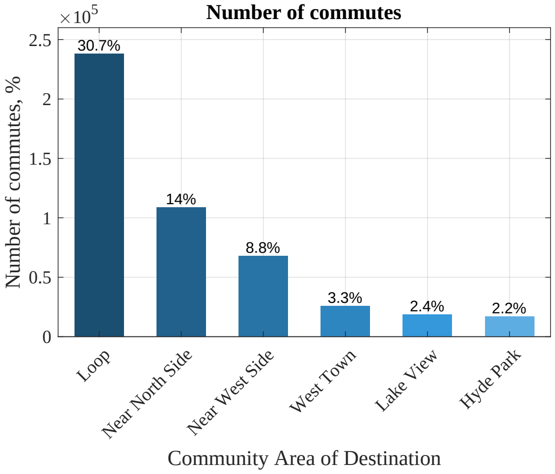

Fig. 9 Destination areas which represent the 60% of the total commutes

III. Methodology

Once the required information about the city of Chicago is introduced in the framework, the next step is to set the stages that this study should follow in order to define the density of air taxis found in Chicago.

At present, there are no UAMstops or related infrastructure in Chicago. The goal of this study is to consider the potential number of UAM flights and airspace density, so we have made assumptions about the location of the UAMstops in Chicago. UAMstops will be located at one of the existing rapid transit system (known as the "L"), because these L stations were distributed around the city with the intent of providing access to the largest number of citizens possible, so the location of these stations - in theory - have considered ease of access. Also, these stations usually possess connections between other modes of transportation, be it bus, train or other subway lines, which ease the access from other more remote areas of the city.

In Chicago there are a total of 140 L stations; thus, two new questions arise. On the one hand, it is important to know which of the L stations will be selected as notional UAMstops, so this work uses the approach that only one L station will be chosen per area (in those areas which possess stations). Similarly, in community areas with more than one L station, only one will serve as the location of the notional UAMstop. To make these selections, the L station closer to the population-weighted centroid of the community area serves as the UAMstop location.

Finally, this study considers four options (Fig. 10) for each commute: drive, public transit, drive+fly, and public transit+fly. The options using public transit include a walk to or from the station, while the drive option assumes (perhaps optimistically) that there are no walk segments. Commuters will choose one of these options depending on the effective cost of the trip, including both the operational cost and the value of time . Therefore, it is necessary to calculate the duration of the trip for each of the options so that it can be finally obtained the feasible number of UAM trips in Chicago.

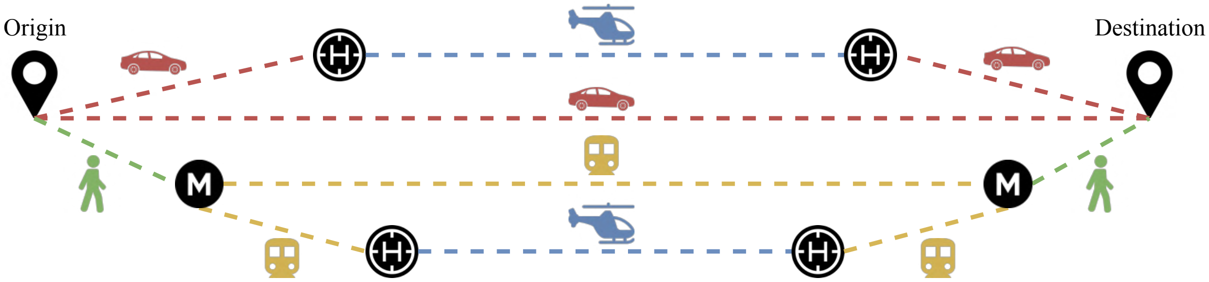

Fig. 10 Commute legs

A. UAMstops location

The first step, as mentioned before, consists of finding the location of the community area centroids in terms of population. Once the centroids are placed for each of the areas (section (II.B)), the distance from those centroids to each of the L stations found in that given community area can be easily computed. Those stations which are closer to the population-weighted centroid of the community area will be selected because, in general, these stations will likely be the most frequently transited. As a result, a total of 42 UAMstops are placed in the locations shown in the Fig. 12:

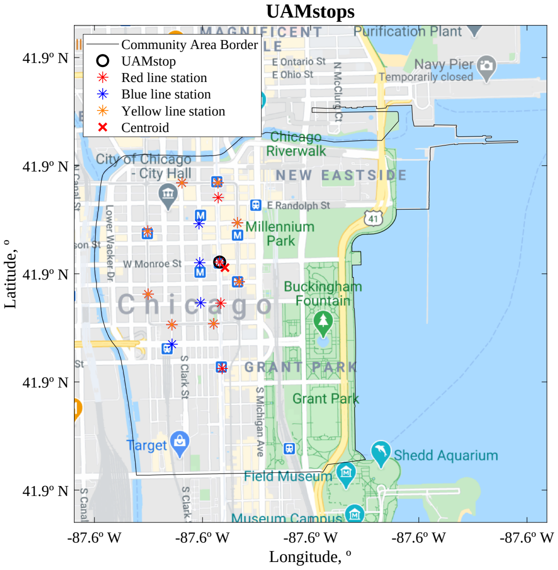

Fig. 11 UAMstops in the Loop Community Area

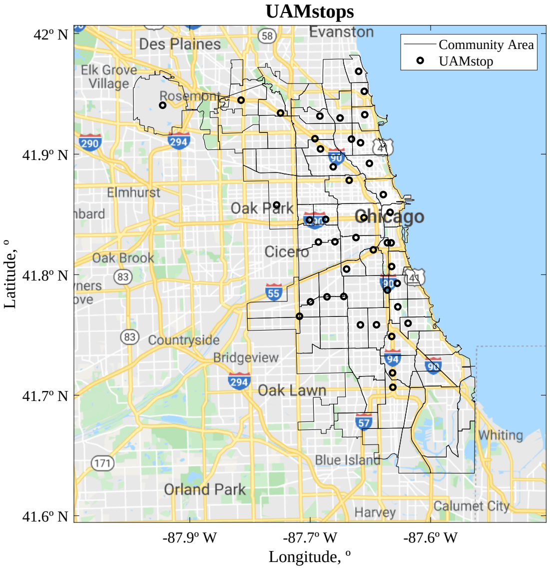

Fig. 12 UAMstops in the city of Chicago

Figure 11 shows the UAMstop corresponds to the L station closest to the population centroid.

B. Flight paths

The aim of this study is to estimate the number of flights resulting from UAM service, so there is an underlying assumption that many features of UAM operations will be feasible. This includes that there will be some form of airspace management in place. Governments and other aviation organizations need to establish new requirements and rules for the future sky that UAM is going to create. As Refs. [10, 11], an integration in the current airspace paradigm is necessary. To produce a more realistic study without attempting to model a full, future urban airspace management approach, some considerations must be taken into account. According to the mission requirements set by Uber Elevate in [3] where the cruise flight level of the nominal aircraft is set to 1500 ft (457 m), possible airspace restrictions or geographical impediments may be encountered.

Nowadays, the airspace is divided into two main segments: controlled and uncontrolled. In the controlled airspace there are five levels or classes: A, B, C, D, and E. Operating in these classes of airspace require Air Traffic Control clearance, and the separation requirements are specifically determined for each Class, along with the allowed flight levels. On the other hand, Class F and G airspace comprise the uncontrolled airspace. In Chicago, there are one Class B and one Class C areas around the Chicago's main airports. Their domains compromise the operation of these new service, because they cover an area between the ground and the flight level that Uber proposes. Therefore, the existence of these restricted spaces set one of the limits for the flight paths.

Chicago is a city that does not have significant geographic changes in altitude; it is a plain with 600 feet of elevation difference between the Lake Michigan and the hills in McHenry County [21]. However, Chicago does impose altitude issues due to its skyscrapers with a current maximum height of 1,450 ft (442 m) flaunted by the Willis tower and followed by the Trump tower which reaches 1,388 feet (423 m). Looking at this, the nominal cruise altitude of the Uber-described UAM [3] is close to the height of these buildings, establishing a new threshold for operations.

The existence of these restrictions will influence the flight path and, thus, the total time of flight. This also means that, the vertical UAM mission profile will not be the same depending on the location of the flight in Chicago according to the requirements set by Uber in [3]. In order to deal with this, we will discretize the airspace of the city by using a mesh with cells of 2150 ft^2 ($200m^2$).

1. Mesh

The height of the tallest object in the area of the mesh cell is assigned to that cell. This height may be either the height of a a building or the altitude of either Class B or Class C airspaces. For this study, the data about the height and the surface of the buildings is not complete, since it has been obtained from Open Street Maps (OSM) which does not contain information about all of the buildings.

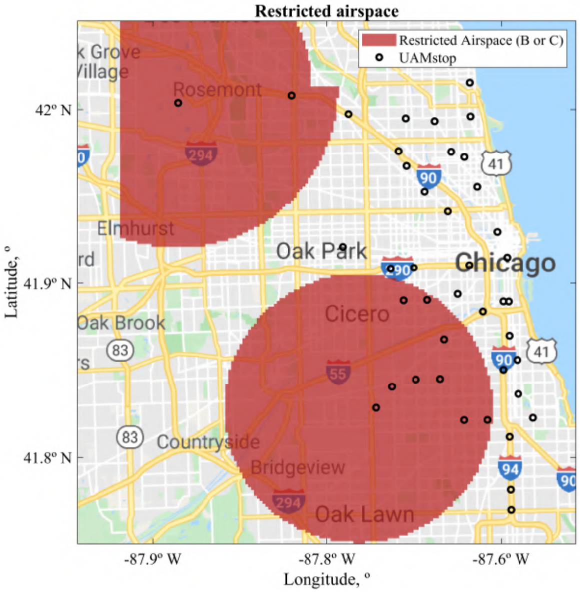

Fig. 13 Restricted Airspace

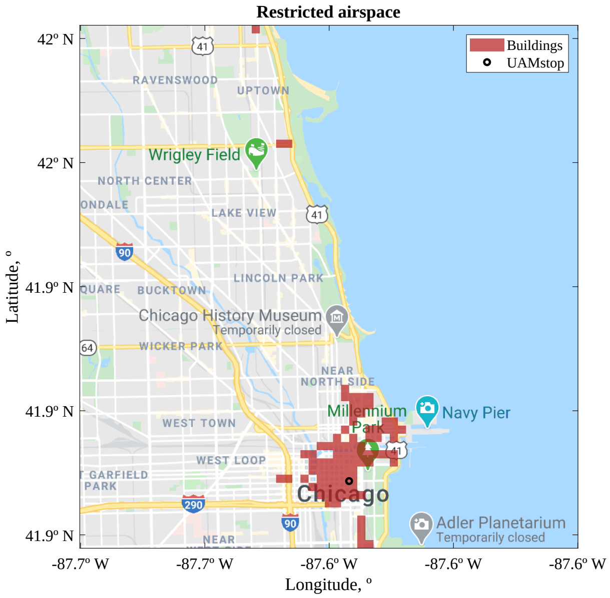

Fig. 14 Restricted Airspace (buildings)

Looking at the location of some of the chosen UAMstops (Fig. 13 and 14), it is obvious that many of them are placed in restricted areas where these air taxis could not access. However, by analyzing the current disposition of the airspace, there are some corridors for VFR flights that allow flights over restricted areas (this corridor idea was also used in [10]). Therefore, we have implemented corridors as a first approach,which allow access for UAM flight to UAMstops in these areas, as Fig. 15 and 16.

In the area of the airports, the corridor has been situated over a highway to take advantage of that infrastructure and avoid obstacles, as well as reduce the noise pollution like it was proposed in [2]. In the downtown area of Chicago, one of the UAMstops is within a restricted cell, thus another corridor has been set (red circle). This corridor idea has been done as a first approach in order to increase the time of flight to add more realism that recognizes the challenges of navigating in this portion of the city. In a study concentrated on locating the UAMstops, this should be made with a different approach, like placing the UAMstop in the rooftop of one building or in an open area like a park.

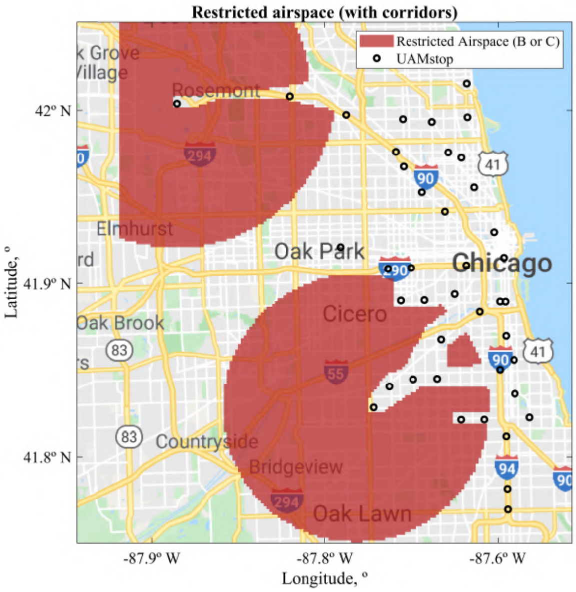

Fig. 15 Restricted Airspace with corridors

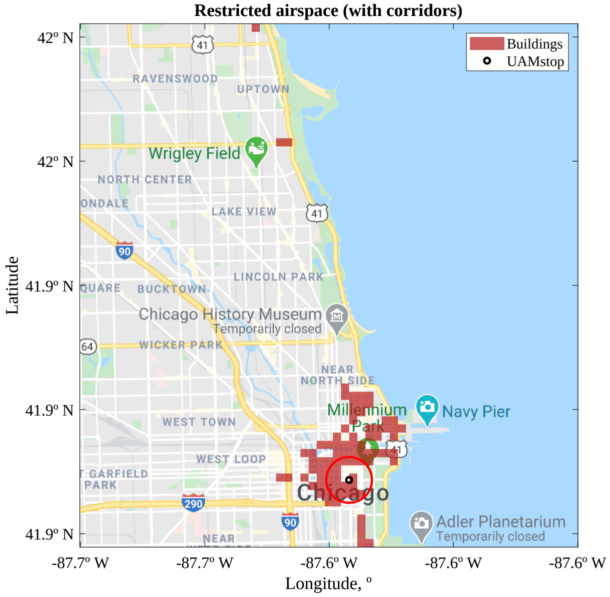

Fig. 16 Restricted Airspace with corridors (buildings)

2. Optimum horizontal path

Once the airspace is divided into cells, we need to define the flight path between UAMStops where aircraft will follow the centroids of the cells, representing waypoints. Since no extra information about these paths currently exists, because they are yet to be defined, Dijkstra's algorithm provides an approach to determine potential flight paths. This algorithm finds the shortest path between two points following a set of predetermined points considering the introduced restrictions limiting UAM aircraft flights.

The restricted cells are those that possess airspace or that have a building with a height over 500 ft (150 m). This height restriction relies upon current VFR rules that say that an aircraft must maintain an altitude of 1000 ft (300 m) over the highest obstacle. Therefore, anything taller than 500 ft, would either need the aircraft to climb above the notional 1500 ft AGL altitude or to deviate.

Therefore, this algorithm defines the optimum paths (Fig. 17) that aircraft flying from one UAMstop to another will always follow. Thanks to this, the distance can be easily calculated but it is still necessary to implement the vertical mission profile which will be explained in the following section.

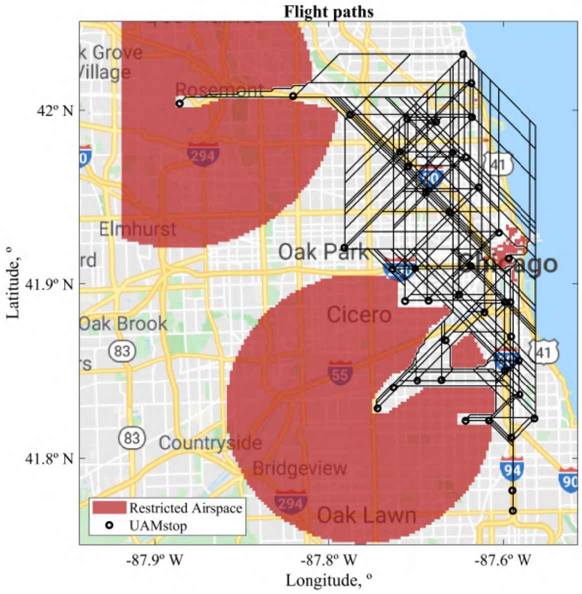

Fig. 17 Optimum flight paths

3. *Vertical mission profile*

Air taxis must reach the maximum possible altitude in order to guarantee safety. In case these vehicles face any problem during flight they must be able to maneuver with enough margin before reaching the ground or any other obstacle. Besides, the closest these vehicles fly to the ground, the highest the noise pollution that they will produce to those living below their flight path. However, the aircraft cannot always reach the desired cruise altitude because the horizontal distance between the origin and destination is too short. In those situations, these vehicles would try to reach the highest possible altitude before starting the descent. In addition, the vertical flight path will depend on the origin and destination, because the presence of airports and tall buildings may influence the climb and approach procedures.

Therefore, different options will be defined (Table 1):

- **Airports**: The ascent in this situation will be made with the lowest vertical speed possible so that the air taxis reach the highest altitude as far as possible from the airport. Besides, after looking at the charts of the Chicago airports, the ascent and glideslope that the airplanes must follow cover a distance of around 4 miles (6 km). As a consequence, after a slight ascent, the UAM aircraft must fly horizontally with an horizontal speed of 150 mph for a distance of 2.48 miles (4 km) (segment D), before starting the climb to the cruise altitude.
- **Downtown**: The downtown area is full of buildings that interfere with the flight path of these vehicles, thus the most vertical ascent/descent must be followed. As a consequence, the horizontal segment that is seen in the mission profile of the airports for the part D is not performed in this case. It will be completely vertical in this situation instead.
- **Remaining areas**: In this situation the ascent/descent will be performed as quickly as possible but without a completely vertical segment, in order to reduce the fuel consumption.

Table 1 Speeds depending on the area

	Airport		Downtown area		Other		
Segment	**Vertical Speed (ft/min)**	**Horizontal Speed (mph)**	**Vertical Speed (ft/min)**	**Horizontal Speed (mph)**	**Vertical Speed (ft/min)**	**Horizontal Speed (ft/min)**	**Ending altitude (ft)**
B	500	0	500	0	500	0	50
C	500	100 (1.2 Vstall)	500	0	500	50	300
D	0	100 (1.2 Vstall)	-	-	-	-	300
E	500	150	500	100 (1.2 Vstall)	500	125	1500
F	0	150	0	150	0	150	1500
G	-500	150	-500	100 (1.2 Vstall)	-500	125	300
H	0	100 (1.2 Vstall)	-	-	-	-	300
I	-300	100	-500	0	-400	50	50
J	-300	0	-300	0	-300	0	0
Vstall	84 mph						

In the following figure is presented the vertical profile according to the area of the city where the departure/approach is performed (they are an approximation and the scale does not match the reality) :

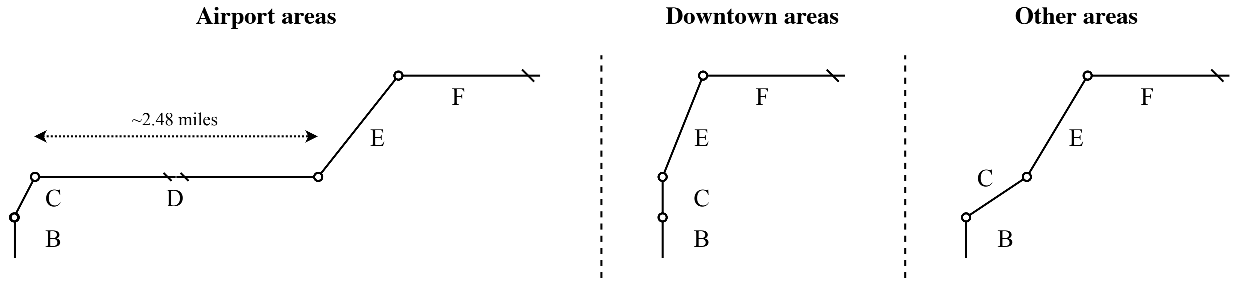

Fig. 18 Vertical profiles

C. Commutes duration

As previously commented, the first option will be driving from home to work without considering the required time to park the vehicle, because we assume that the commuter will have a parking spot reserved both at home and at his/her work location. The second option will be using public transit (bus, train or subway) where the time includes a walk to the stations of the public transit or to perform the necessary transfers. The last two include part of the trip that uses an air taxi. Thereby, those trips are divided into three parts that Fig. 10 above shows (we consider walk and transit together as one segment). When public transit is used in the two remaining parts of the trips, the same assumptions used for a complete public transit trip will be applied. However, when driving is the option to complete the trip after the air taxi segment, we consider a service where the carrier provides the option of using on-demand cars like the current ride share services like Uber or Lyft, or even the future autonomous cars.

To compute the required amount of time for each of the trip options this study uses a tool developed in Java known as *Open Trip Planner* (OTP) following the procedure explained in [22, 23]. This tool uses both data of the map of the city and the timetables of the public transit. *Open Street Maps* (OSM) is a collaborative and open project for the creation of maps, thus contains information about streets, buildings, etc. Finally, for the public transit schedules, CTA, Metra and Pace are the organizations in charge of this information. Therefore, after introducing this information on the OTP tool, an API is created that contains all this information, so that we can create a query with Matlab containing all the required parameters like origin and destination of the trip, mode of transport or arrival time.

For the driving and transit option, we can just set the origin and destination coordinates and the desired arrival time. However, for those trips which contain an air taxi part, the procedure is slightly different. The trip is divided into three sections, and the middle one is not computed by the API, but is introduced by our Matlab code. Therefore, we need to start from the last part of the trip, which consists of the path from the destination UAMstop to the destination. This approach allows us to know when the commuter needs to leave the destination UAMstop in order to reach his/her destination at the specified arrival time. This departure time from the UAMstop, provides the required arrival time of the flying leg. Because the time of flight is known (presented in section III.B) we can then determine the required departure time of the air taxi from its origin UAMstop. This departure time indicates the required arrival time to the origin UAMstop from home, which provides the necessary departure hour from home. For the air taxi part of the trip, we have to add a waiting, warm up, and boarding/deboarding time, which for this study has been chosen as 4 minutes for boarding/deboarding time and 2 minute for warm up time, resulting in a total amount of 10 minutes, alike in previous studies where it was chosen as 10 minutes [13].

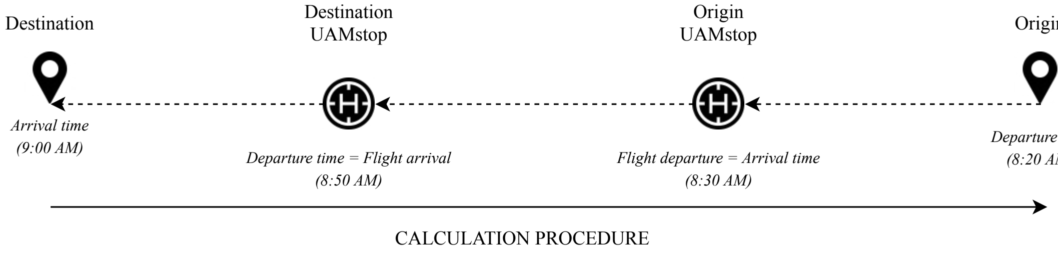

Fig. 19 Commutes calculation procedure

We will also increase and decrease the amount of time spent in the UAMstop to observe the difference in the results and to introduce the ride-sharing option. Therefore in this second scenario 5 minutes for each part is selected establishing a total of 20 minutes, followed by another scenario with 1 minute for warm up and 2 minutes for boarding/deboarding constituting a total of 5 minutes.

Thereby, we will analyze the following cases:

- **Scenario 1:** 5 minutes in the UAMstop
- **Scenario 2:** 10 minutes in the UAMstop (main scenario)
- **Scenario 3:** 20 minutes in the UAMstop

The same scenarios but with the time distributed to include ride-sharing will be also studied:

- **Scenario 4:** 10 minutes in the UAMstop with ride-sharing
- **Scenario 5:** 20 minutes in the UAMstop with ride-sharing

After applying this comparison, we are able to obtain the trip duration depending on the mode used for commuting. The examples presented in Fig. 20 and 21 represent scenarios 2 and 4 respectively and show that the fastest method uses

VTOL UAM aircraft and a car to travel to the destination, whereas driving would be the second one.

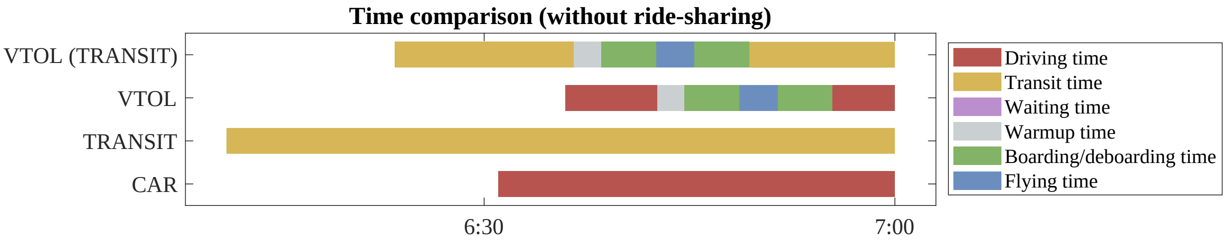

Fig. 20 Commutes time comparison example with 7:00 am arrival time (without ride-sharing)

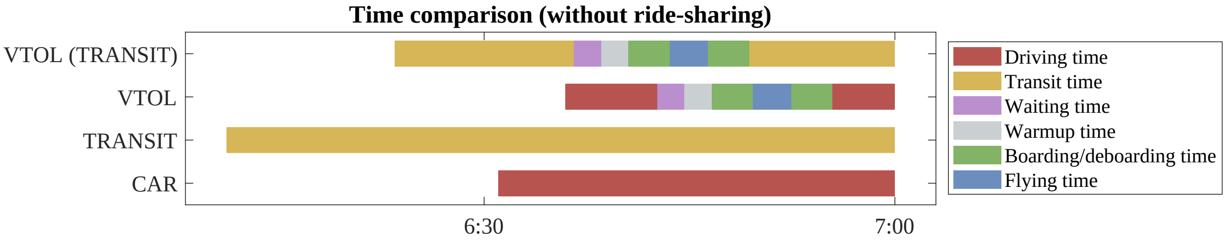

Fig. 21 Commutes time comparison example with 7:00 am arrival time (with ride-sharing)

D. Comparison method

The effective cost allows comparison of the different options: drive, public transit, fly+drive or fly+public transit. This approach has been taken from [4–6], where they propose that the cost of a trip is compound by the operational cost (it depends on the chosen option), together with people's value of time. However, this last component of the effective cost is not consistently defined in the existing literature, and is known to have significant uncertainty. Therefore, as a first approach, the value of time is related to the hourly income of the citizens in the city of Chicago, previously presented in section II.C. The metric will be then:

$$Cost_{eff,i,j} = Cost_{oper,i,j} + Cost_{time,i,j} \tag{1}$$

$$Cost_{time,i,j} = time_{trip,i,j} * time_{value} \tag{2}$$

where:

$$Cost_{eff,i,j} \ - \ \text{Effective cost for the mode i and the trip j} \tag{3}$$

$$Cost_{oper,i,j} \ - \ \text{Operational cost for the mode i and the trip j} \tag{4}$$

$$Cost_{time,i,j} \ - \ \text{Cost due to the value of time for the mode i and the trip j} \tag{5}$$

$$time_{trip,i,j} \ - \ \text{Total door-to-door trip time for mode i and the trip j} \tag{6}$$

$$time_{value,i,j} \ - \ \text{Value of time of the passenger} \tag{7}$$

In this effective cost model to describe the traveler's trip choice, $Cost_{oper}$ would be the cost of operating a personal vehicle, the cost of buying a ticket for public transit or for the UAM flight. By referring to this term as operating cost, we do not necessarily mean to imply the operator of the public transit or the UAM flights, it simply passes along the vehicle operating cost. Profit margin for a private UAM operator or subsidy for a public transit operator might make the ticket price higher or lower than the actual vehicle operating cost.

After calculating the effective cost for each of the trips, the option which presents the minimum value in terms of cost will be the chosen one. This approach also assumes that the trip-taker makes decisions in a wholly economically rational approach. Thereby, the trips can be classified according to the selected mode of transport, and the goal here is to determine how many trips utilize the UAM aircraft.

E. Computational framework

All these elements and sections previously explained are joined in a computational framework that has been created using mainly Matlab, although it also uses extensions implemented in Python and Java. Thereby, this computational tool that we have created consists of 6 modules that predict the density of air taxis based on commute trips from home to work:

- **Module 1 - Read data**: Through this module, our program is able to obtain the data previously presented about the income, commutes, boundaries of the city, CTA, population, congestion, etc.
- **Module 2 - Dataset creation**: This module uses the data previously obtained to generate the dataset defined as *commutes* and *community_area*. To do so, functions for the probability of a commutes or the congestion of traffic are implemented for the generation of the commutes dataset. In order to produce the second database, other functions are utilized which calculate the income, population, centroids, as well as UAMstops of the city.
- **Module 3 - Airspace mesh**: This module discretize the airspace creating the mesh commented in III.B. It also gets information about the buildings and the airspace classification.
- **Module 4 - Flight path**: With this module the optimum flight paths are created using the Dijkstra algorithm and data from the *commutes* and *community_area* database, so that a new dataset is generated known as *flight_path*.
- **Module 5 - OTP**: This module uses the OTP tool to generate the trips duration and data from the *flight_path* dataset and saves that information in the *commutes* database.
- **Module 6 - Density**: Thanks to information generated in the module 5, this last one is able to determine the density of aircraft in the Chicago airspace by using the effective cost metric.

To better understand these module, the following scheme has been generated.

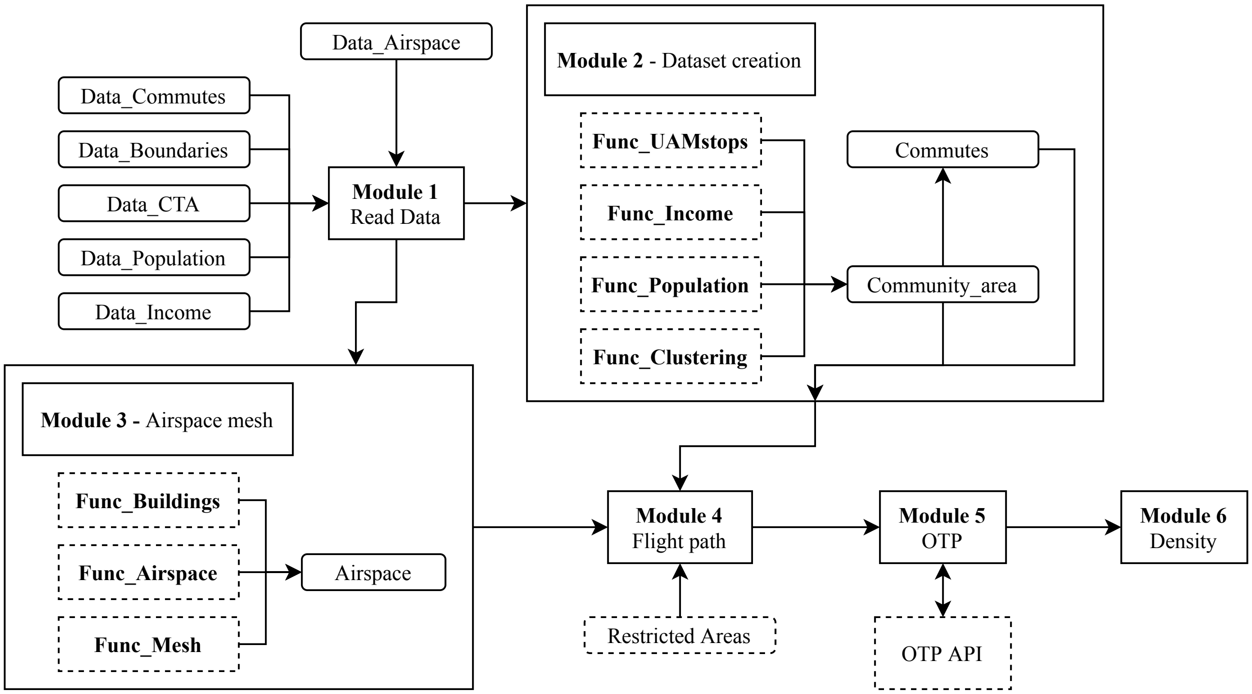

Fig. 22 Computational framework

IV. Result Summary

This last section presents results predicted by this framework. To do so, three different scenarios will be analyzed using UAM operating costs based upon three time frames from the introduction of the UAM service as presented by Uber in [2]: initial term, short term and long term. These three stages differ in the operational cost of the service due to improvements in the technologies or in the level of autonomy, along with the introduction of an economy of scale that lowers the cost of production and operation of these air taxis.

The operational cost according to Uber is:

- Initial term: \$5.73/(pax-mile)
- Short term: \$1.86/(pax-mile)
- Long term: \$0.44/(pax-mile)

The cost of driving a car has been fixed to \$0.575/mile based upon reimbursement rates [24], whereas the cost of public transit has been set to \$2.5 (the cost of one-way ticket) using the CTA.

A. Modes of transport demand

To create a dataset of home-to-work commute trips, we can use the provided origin and destination of actual trips; however, we use a random selection of the arrival time from the distribution shown in Fig. 3, because the commute trip data does not include specific time information. However, the results should not be highly influenced by this selection of arrival times, because we seek to obtain a general view of the number of air taxi trips selected under the three operating cost scenarios. Using the data for the scenario number 2, the following distribution of the 657,627 home-to-work commute trips are obtained:

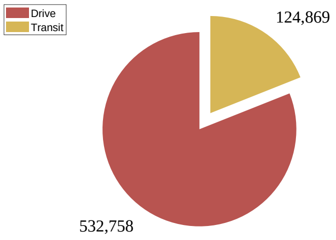

Fig. 23 Number of trips using initial cost

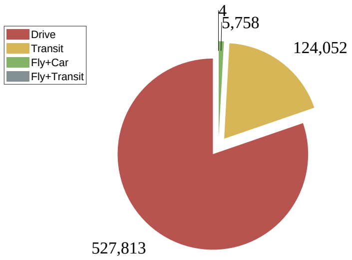

Fig. 24 Number of trips using short-term cost

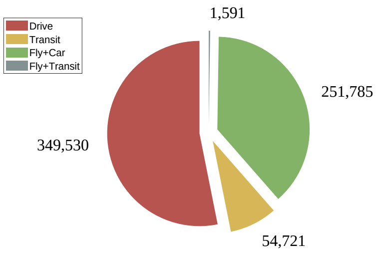

Fig. 25 Number of trips using long-term cost

Looking at the previous charts, Fig. 23 clearly shows that using UAM for the selected region of Chicago and for the cost provided by Uber is not feasible in the initial term. The main mode selected in this case is driving with 552,758 commuters, whereas the public transit is left for a total of 124,869 citizens.

However, when the cost of operation is reduced to the value of the short term, the number of users of this service increases. Specifically, it reaches 5,758 commuters when a car is used to get to the UAMstop, whereas just 4 commuters will utilize this option with public transit as the transfer service.

Finally, in the long term, when the cost is decreased to \$0.44/(pax-mile), which is lower than the cost per mile of the car trip, the number of commuters of UAM increases significantly, producing a complete change in the paradigm. In this situation, the number of citizens using UAM is almost the same than those using the public transit with 251,785 for the combined Flight+Car and 1,591 for Flight+Transit.

The results here, using our modeling approach, show that combining public transit and UAM service is not viable, at least for the current location of the UAMstops and the selected radius of influence (for instance, if our study included a larger portion of the outlying Chicago metropolitan area, perhaps UAM would be feasible for some travelers using the initial cost). Another aspect that can be decisive in the obtained results is the selected waiting, boarding/deboarding and warming-up time, which increases the total time of flight. This selection could highly increment the total number of trips, even for the initial term, which could be mainly directed to longer trips at the beginning. In addition, it must be commented that each trip represents one person, thus no ride-sharing has been introduced. Implementing this option would reduce the price of the trips for the individual traveler, but this would likely come with an increase in the wait time to allow for multiple passengers to collect at the UAMstop and board the aircraft. This is a trade-off that should be found, but that is beyond the goals of this project. It also would reduce the number of aircraft in the airspace at a given hour. While it is not a complete ODM service, the UAM ride-sharing could have a similar approach to the one used by BlaBlaCar, the French carpooling service, where the user is able to select the timeframe for the trip together with the origin, destination and rider.

B. Airspace density

The previous section presented an estimate of the number of home-to-work commute trips that would use UAM for part of the trip. We used this estimate of number of trips to compute an airspace density. In our case, knowing that the city of Chicago covers an area of 177 nmi^2 (606 km^2), we can obtain a distribution of the airspace density using the home-to-work commute trips. Figure 26 shows this density at each hour of the day using the short-term costs, and Fig. 27 shows this using long-term costs. These figures use very different scales on the vertical axes. The shape of the density distribution over time matches the shape of the arrival time distribution in Fig. 3, with a peak during the traditional morning rush hour.

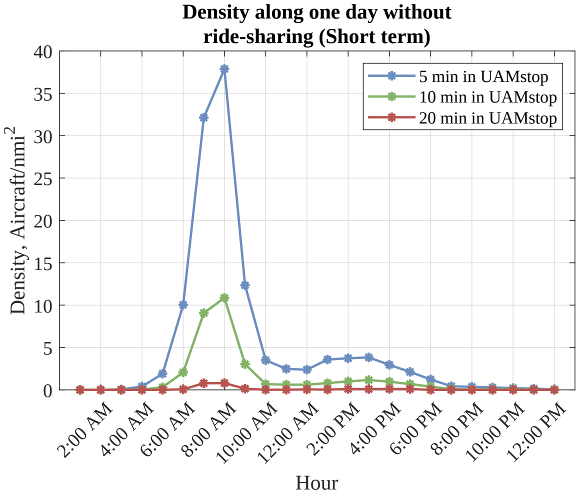

Fig. 26 Density along one day (short term)

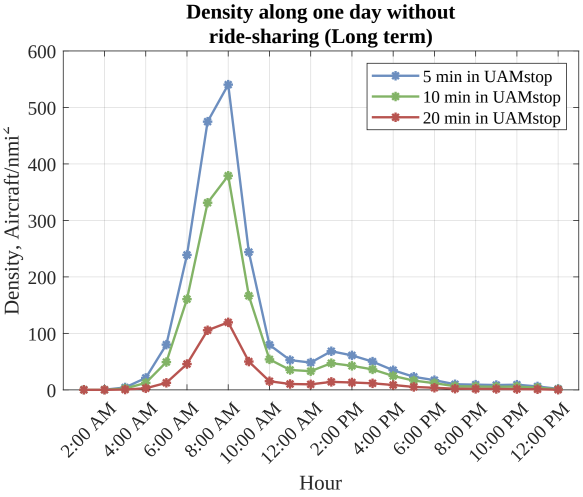

Fig. 27 Density along one day (long term)

In this two figures we have also represented a comparison in the density depending on the amount of time spent in the UAMstop. Therefore, we are able to see a reduction in the density due to the increase of the duration, which directly affects on the number of feasible trips. This influence is more remarkable when considering the short-term costs where a huge step appears between using the five minute and ten minute time the commuter spends in the UAMstop.

Using the assumption that each commuter triggers a UAM flight, so there is one passenger per aircraft, leads to the curves presented in both figures. From this, we obtain the following maximum UAM airspace densities:

Table 2 Maximum airspace density

	5 minutes	**10 minutes**	**20 minutes**
Initial cost	0.017 aircraft/nmi^2	0 aircraft/nmi^2	0 aircraft/nmi^2
Short-term cost	38 aircraft/nmi^2	11 aircraft/nmi^2	0.8 aircraft/nmi^2
Long-term cost	540 aircraft/nmi^2	380 aircraft/nmi^2	120 aircraft/nmi^2

For comparison, Mueller et al. use a UAM-related airspace density of one aircraft per square nautical mile and provide a traditional peak airspace density ranging from one aircraft per 250 nmi^2 to 500 nmi^2 [10]. Our prediction using the short-term cost values is consistent with this estimate, but our prediction using the long-term (lower) cost values is four orders of magnitude higher. Our values assume no restrictions or constraints on the airspace or at the UAMstops, but this suggests the possibility for density that would likely be unattainable.

Our previous hypothesis states that each commuter triggers a UAM flight, but most studies – including Uber elevate – recognize that ride-sharing would be part of UAM operations. This might suggest that these peak densities overestimate the potential future density. However, in our model, ride-sharing would reduce the cost of the trip using UAM; in turn, a lower cost UAM trip – even with a higher wait time for boarding – might lead to a lower effective cost, so that this would not simply reduce the number of flights by half.

Conducting the study to add wait time to collect multiple passengers and consider the lower cost per passenger for the UAM trip was not part of this study, but it would be the more rigorous way to consider UAM airspace density. As a simpler approach here, we converted two UAM trip segments between the same UAMstops within the same time window into a single UAM trip. This leads to the dashed curves in Figs. 28 and 29, with the peak densities presented in the Table 3.

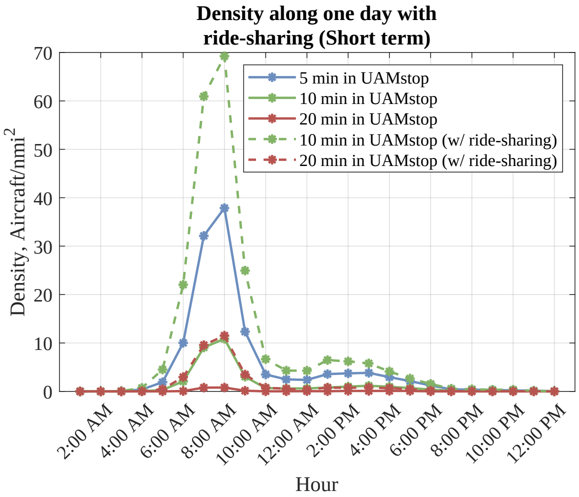

Fig. 28 Density along one day with ride-sharing (short term)

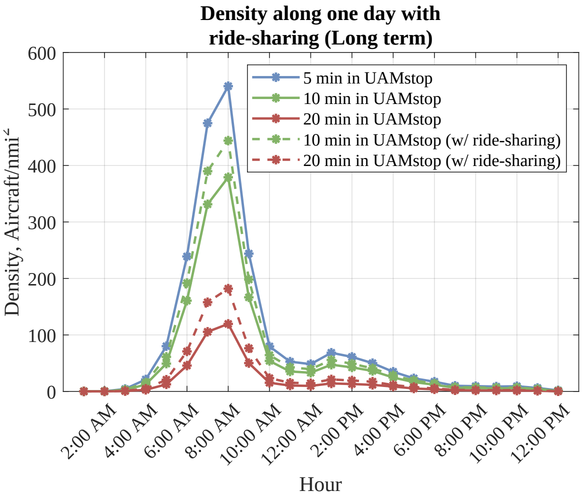

Fig. 29 Density along one day with-ride-sharing (long term)

Figs. 28 and 29 show that the main improvement related to implementing our simplistic representation of ride-sharing is found in the short-term, where the maximum density for a 10 minute time to coordinate passengers for ride-sharing almost doubles the density for a five minute single-passenger wait in the UAMstop without ride-sharing. This fact corroborates that ride-sharing plays an important role when trying to spread the UAM service to a wider number of commuters in the short-term, since its influence in the long-term is insignificant. Besides, this aspect is reaffirmed when looking at the results for 20 minutes with ride-sharing which reaches a value almost equal to the one for 10 minutes without ride-sharing.

However, it is important to highlight that the scope of this study does not focus on the ride-sharing influence. Therefore, this aspect has been presented as an introduction to a future study centered in the optimization of ride-sharing. We have tried to be conservative in this analysis just considering those commuters in the same window but we could have played with the waiting time in order to match more trips, which would have increased the final density.

Table 3 Maximum airspace density with ride-sharing

	10 minutes	**20 minutes**
Initial cost	0.5 aircraft/nmi^2	0.01 aircraft/nmi^2
Short-term cost	69 aircraft/nmi^2	12 aircraft/nmi^2
Long-term cost	444 aircraft/nmi^2	182 aircraft/nmi^2

Finally, this study only considered the home-to-work commutes, and the work-to-home commutes is not exactly symmetric, nor does this include other non-commute trips, so the peak airspace densities here are illustrative and indicative of the potential UAM traffic, but are not definitive.

C. Trips statistics

Once, the total number of trips and the density of the airspace have been set, some statistical characteristics can be extracted from the results. Because no flights are predicted for the initial term cost and because the number of transit+fly trips in the short-term is really small, this section focuses on the long-term cost.

1. Duration of the trips

The average duration of the feasible UAM trips in the city of Chicago is the first important descriptor from the generated data. Looking at Fig. 30 and 31 the duration of the trip along the day appears quite constant, for both mode combinations of *Fly+Transit* and *Fly+Car*, even when short- and long-term costs are compared. Nevertheless, the public transit option presents a more oscillatory result, because for some hours of the day, no trips combining public transit with UAM are generated. Recall that with the short-term pricing, no trips combine public transit with UAM.

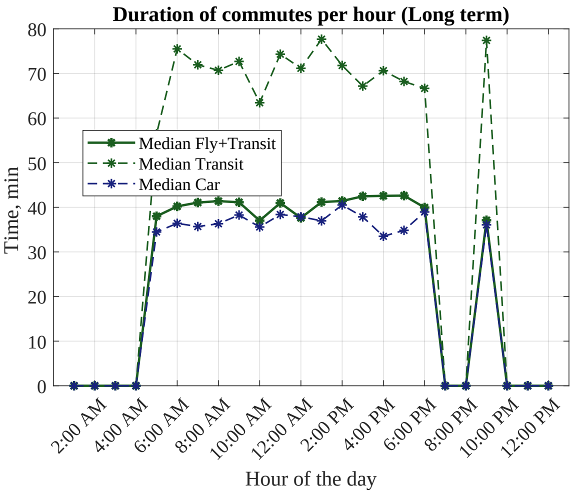

Fig. 30 Duration in the long-term (transit)

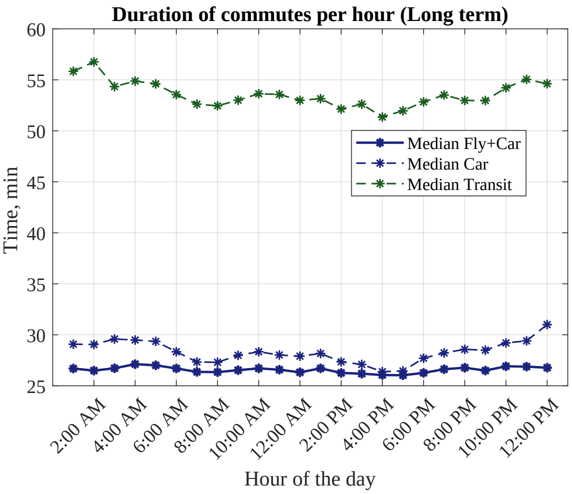

Fig. 31 Duration in the long-term (car)

A tendency is found after analyzing these plots, because 40 minutes seems to be the typical duration for the fly+transit combination, whereas commute trips using fly+car have a nearly similar duration of around 26 minutes regardless of the other ground traffic and the hour of the day. However, we do see an increase of the time of some trips in the rush hours, following the tendency presented in Fig. 3, as a consequence of the traffic congestion.

One important fact here is that in the fly+transit option no UAM-using trips are generated "overnight". This can be a consequence of two reasons. Firstly, the number of trips generated at those hours is lower, which decreases the probability of finding a feasible trip in comparison with other cheaper options. On the other hand, the traffic congestion at those hours can be stated as practically non-existent, which stimulates other legs.

In these previous figures, we have also represented with dashed lines the median of the duration for the same trips using ground-only options in order to see the time savings. For the long-term, when the fly+transit is used, the time savings versus using transit-only is huge (around 35 min). However, when this duration is compared with the median of the same trips using a car, the duration is even bigger with the fly+transit. In this case, is the cheaper operational cost of transit is what makes fly+transit more feasible.

Looking at the results of the fly+car combination, the time savings with respect to just driving are around five minutes. These time savings are expected to be even higher for the transit-only option, which in this case is around 30 minutes lower.

Finally, it is important to highlight the appearance of trips with a higher duration at the rush hours of the day, since these new urban air services become more feasible than the traditional ones, typically congested at those hours.

2. Distance of the trips

The duration of a trip highly depends on its distance, since it increases with the range, although it is directly influenced by the location of the origin and destination UAMstops. As presented before, the vertical mission profile changes if the UAMstop is located at the downtown area or at an airport (Fig. 18).

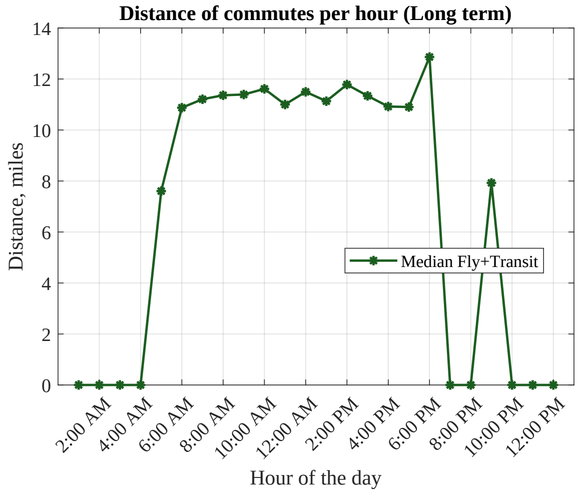

Fig. 32 Distance in the long-term (transit)

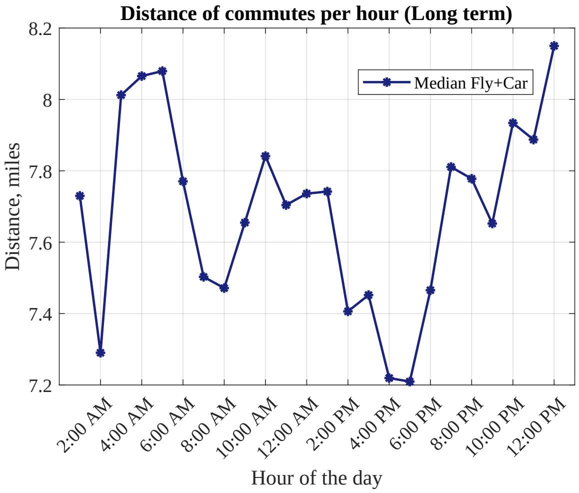

Fig. 33 Distance in the long-term (car)

In order to make this study more relevant, we will only focus on the 2D path, or in other words, the point-to-point distance from origin to destination.

Looking at the results presented in Fig. 32, the median of the distance for the fly+transit combination is located around 11 miles. As expected, it follows the same distribution previously presented where no trips where found "overnight". However, focusing on the fly+car combination, the median of the distance is kept practically constant for all of the day with a value of around 7.7 miles. Unlike the fly+transit combination, these trips are distributed along the whole day and not only at the rush hours. Even so, at around 7 am and 4 pm the typical distance of this commutes is reduced because of the traffic congestion found in other modes of transportation , as presented in Fig. 3.

3. Effective cost of the trips

The number of feasible trips which implements a flying part is not only influenced by their duration or their distance, but also by the effective cost of using this service (operational cost + value of time). As a consequence, it is relevant to study the average of the cost along one day.

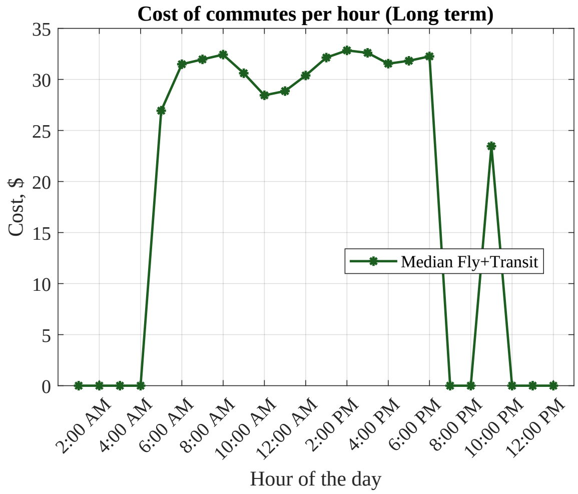

Fig. 34 Cost in the long-term (transit)

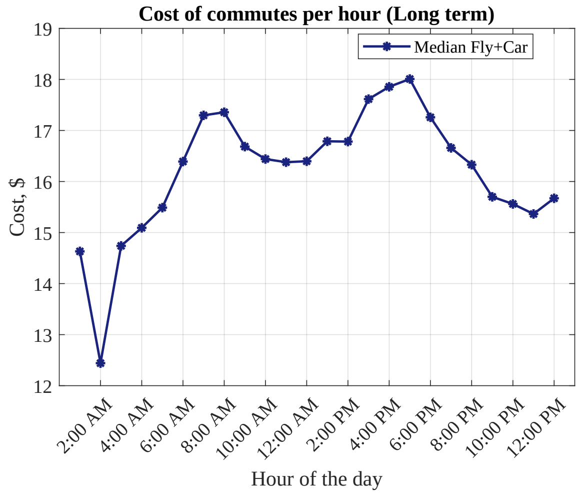

Fig. 35 Cost in the long-term (car)

In this case we can see that the curve follows a slightly different shape regarding the previously seen plots. This is because the effective cost is directly proportional to the duration of the trip but it also depends on the value of time.

After seeing the exposed plots, it is evident that the average cost during one day, in the long-term, for the fly+transit combination presents a value of around \$33. Looking at the Fig. 35 we can see that again the fly+car combination presents a value practically constant for all of the hours of the day which is around \$15. In this scenario, we can see a bigger fluctuation in comparison with the previous plots.

However, the effective cost is the compound of two terms and one of them highly depends on the passenger's value of time. We are going to present in the following pictures how the commuters value the time for those trips.

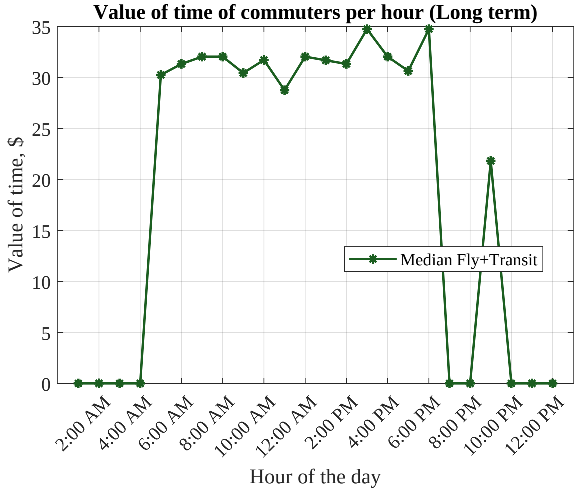

Fig. 36 Value of time in the long-term (transit)

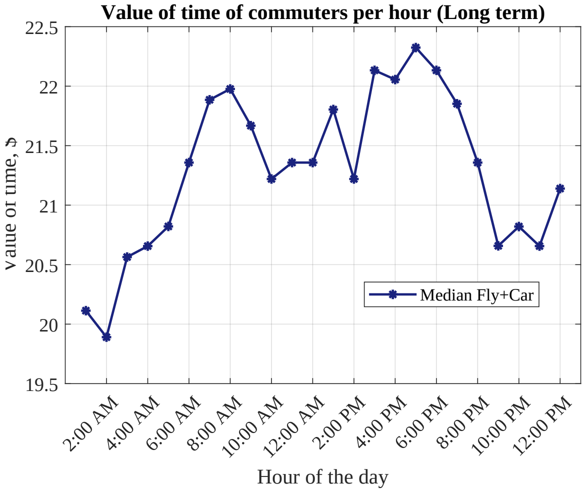

Fig. 37 Value of time in the long-term (car)

The value of time of commuters using the fly+transit option is higher since this mode usually requires more time. Thereby, population using this service must have a higher value of time, which in this case is located at around \$33. On the other hand, people which use a car as the transfer mode, have a lower value of time because this mode is usually faster.

To conclude this section, we must comment that analyzing the tendency of the duration, distance and cost is complicated due to its dependency on many factors and because they are strictly linked to each other. However, some characteristics have been confirmed after looking at these results since, as expected, the effective cost of using the fly+transit mode is higher, therefore the value of time of those commuters must be higher. In general, there is a reduction in the average duration, distance and cost when using the fly+car service since the duration of the trip is smaller and the accessibility of this option is usually higher. Many parts of the city are not well-connected to the public transit, decreasing the number of feasible trips.

V. Conclusion

This study demonstrated a computational tool that is able to estimate the number of UAM operations in the city of Chicago by using information like: number of commutes, traffic congestion, population, mean population income, airspace classification, buildings height, and travel trends, and making the trip mode choice based on our effective cost metric. The results of the computational tool allows prediction of home-to-work commute demand distribution within the city during one day by selecting the origin and destination location. In addition, the approach can predict the number of operations at a given UAMstop. As previously shown, the number of commuters using this service is 5,762 and 253,376 in the short- and long-term respectively. The airspace density originated by those values in the short-term and long-term reach a peak of 11 aircraft/nmi^2 and 380 aircraft/nmi^2 in our main scenario, where no ride-sharing is considered.

This study mainly shows the viability of implementing this service within the city boundaries for the short- and long-term definitions that Uber Elevate specifies. Therefore, in order to introduce this service in the initial scenario, a wider area should be considered (like the Chicago metropolitan area). The generated database show that the average duration of the trips is around 30 minutes when cars are used as a connection to travel from/to the UAMstops, whereas around 50 minutes are required when the connection is public transit. In addition, this study shows that an ODM ground service (e.g., the current Uber or Lyft approach) play an important role so that this service can be viable, specifically the combination of driving and flying.

Finally, future work should be performed regarding the location of the UAMstops, like for example implementing the current infrastructure or by directly using the population centroids as the location of the station of this new service. The warm-up, waiting and boarding/deboarding times defined in this study together with the ridesharing require further study.

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