7-2021

Monte-Carlo-Based Analysis of Traffic Flow for Urban Air Mobility Vehicles

Sara Ghayouraneh
University of Arkansas, Fayetteville

Monte-Carlo-Based Analysis of Traffic Flow for Urban Air Mobility Vehicles

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy in Engineering with a concentration in Electrical Engineering

by

Sara Ghayouraneh
University of Tabriz
Bachelor of Science in Electrical Engineering, 2014
University of Tabriz
Master of Science in Electrical Engineering, 2016

July 2021
University of Arkansas

This dissertation is approved for recommendation to the Graduate Council.

Samir M. El-Ghazaly, Ph.D.
Dissertation Director

James M. Rankin, Ph.D.
Committee Member

Cynthia Sides, Ph.D.
Committee Member

Jingxian Wu, Ph.D.
Committee Member

Jeff Dix, Ph.D.
Committee Member

Abstract

The research conducted in this dissertation is focused on developing a simulation tool that can predict the traffic flow patterns of the Urban Air Mobility vehicles to alleviate some of the challenges related to their traffic management. First, an introduction to the concept of Urban Air Mobility is given, the usage of Automatic Dependent Surveillance-Broadcast systems for Urban Air Mobility vehicles is suggested and dynamic addressing concept is introduced as an answer to a part of air traffic management and address scarcity challenge for Urban air Mobility vehicles. Next, in order to simulate the traffic flow patterns of the Urban Air Mobility vehicles, a Monte-Carlo-based simulation tool is developed, and the simulation results are analyzed for two different cases. These results lead to the proper observation window for the simulations and a solution to determine the approximate number of addresses needed to accommodate the desired number of Urban Air Mobility vehicles, which would be a solution for the address scarcity problem of the Urban Air Mobility vehicles.

Furthermore, multiple scenarios of different policies, flexibilities, and their impact on the distribution of the number of active Urban Air Mobility vehicles throughout the day are observed. Results show that decreasing the maximum allowed flight duration in the busy periods of the day is proved to reduce the number of active Urban Air Mobility vehicles. Also, the effect of static and dynamic denials is observed and concluded that the static-denial approach alleviates the traffic faster, but the dynamic denial alternative is more fair, equitable, and adaptable as it offers the clients the option to be waitlisted. Overall, the dynamic-denial approach offers better customer service compared to the static one, and the price adjustment case is the most effective and flexible approach. Moreover, three different scenarios are introduced to observe the cases where the Urban Air Mobility vehicles are able to make both inter-city and intra-city trips. The three scenarios are

focused on inter-city cases and consist of cases where the inter-city travelers (1) release their address at the border, (2) keep their addresses while crossing the border, and (3) use a shared address pool. The developed analysis tool using the Monte-Carlo simulation technique predicts the results and the outcomes of the three scenarios are compared using the introduced figures of merit. According to the observations, each scenario has its own advantages and possible limitations. Based on the situation, the air traffic management can examine the options and develop the most suitable policy.

Acknowledgement

I would like to express my deepest appreciation and gratitude to my Ph.D. supervisors, Dr. Samir El-Ghazaly and Dr. James Rankin, for their patience and assistance throughout this entire journey. Beside their endless professional support, they taught me the life lessons that I would not be able to grasp anywhere else.

Also, I would like to acknowledge my dissertation committee members, Dr. Cynthia Sides, Dr. Jingxian Wu, and Dr. Jeff Dix for their support and motivation and assisting me in accomplishing all my objectives in this path. They have always made me feel very welcomed when I was in need.

I would also like to thank Dr. Fred Limp whose warm and welcoming nature, patience, and knowledge creates a wonderful class environment for his students.

Also, I would like to thank James Flammer and Kim Russel, who always lent a sympathetic ear when I needed one.

Dedication

To the loving memory of the victims of Flight PS752

Table of Contents

List of published papers

Chapter 2: Ghayouraneh, S., Rankin, J. M., and El-Ghazaly, S. M., “Dynamic Addressing for Urban Air Mobility Vehicles,” Journal of Air Transportation, Vol. 28, No. 4, 2020, pp. 1-4.

Chapter 3: Ghayouraneh, S., Rankin, J. M., and El-Ghazaly, S. M., “Monte Carlo Simulations to Predict Traffic Flow Patterns of UAM Vehicles,” Journal of Air Traffic Control, Vol. 62, No. 3, Nov. 2020, pp. 46-54.

Chapter 4: Ghayouraneh, S., Rankin, J. M., and El-Ghazaly, S. M., “Monte-Carlo-Based Analysis of Inter-City and Intra-city Travels of UAM Vehicles,” Journal of Air Transportation. (Submitted)

Chapter 1

Introduction

1.1 Urban Air Mobility Vehicles and Associated Traffic Management Challenges

As the population grows, especially in larger cities, people waste a great amount of their day in heavy traffic and there is always a struggle to find different ways to reduce this. People in San Francisco are wasting an average of 230 hours per year in traffic going to work and coming back home and this means losing half a million hours of productivity per day. This wasted time increases to seven weeks per year for people in Los Angeles. The huge amount of commute time causes a high level of fuel consumption and air pollution, spending less time with family, having less time at work which affects the economic growth, and a high level of stress [1]. Although much has been done to help make the traffic lighter, population growth and people's preference to use their personal cars are making the megacities more crowded each day. Therefore, the idea of Urban Air Mobility (UAM) or On-Demand Mobility (ODM) is introduced to be a potential solution for traffic congestion [2]. Based on this idea, air transportation and UAM vehicles (shown in Fig. 1) will be involved in a part of an urban transportation system and can be an efficient and quiet way of transportation [3]. Studies have shown that a commute time of two hours from San Jose to San Francisco can be reduced to 15 minutes with these UAM vehicles [1].

Research has continuously emphasized on the importance of on-demand urban air transportation and has discussed about various critical challenges that will appear while moving forward through the future urban transportation in the air. These challenges, which are considered from both design and air traffic management perspectives, have been explained in full details and some possible solutions suggested. Furthermore, a broad view as a starting point to think about the path to urban air-transportation systems and UAM vehicles has been given [1]. The concept of ZIP

Aviation which enables new markets for aviation and creates more flexibility than the other ways of transportation has been introduced. The importance of electric propulsion and autonomy which offers a chance to provide new high speed and On-demand transportation alternatives that can eliminate the huge costs needed to be invested in ground-based infrastructure has been discussed [2]. The concept of UAM along with some technical improvements associated with airspace integration has been highlighted [4-6]. Furthermore, various approaches regarding enabling the existing system to support the UAM-related traffic management system have been discussed [3]. Moreover, a broad view of the predicted UAM services has been given to indicate operational restrictions and examine the short and long-term alleviation opportunities. Policies and legal challenges regarding the acceptance of community, impacts on the environment, and flying in lower altitudes have also been discussed [7].

Fig. 1 A UAM vehicle flying over a city (From cheskyw/123RF)

Currently, the structure and design of the airspace defined by Federal Aviation Administration (FAA) do not have enough flexibility to allow a new air transportation system as UAM and a great effort is needed to allocate the airspace to different air transportation systems [7]. Nowadays, Unmanned Aerial Systems (UAS) are flying at an altitude range below 400 feet where few, if any, manned aircraft are flying. With Unmanned Traffic Management (UTM) and

Detect and Avoid systems (DAA), UAS are able to communicate with each other with a minimum collision risk [8-12]. However, urban air mobility vehicles are expected to fly at the altitude of 1000-3000 feet above ground level, which requires the UAM vehicles to communicate among themselves and with other aviation-related vehicles flying in that range [3]. Since UAM is recognized as a manned transportation, there will be a higher risk of collision compared to unmanned vehicles and, therefore, there is a need for an Air Traffic Management-like (ATM-like) or Unmanned Traffic Management-like (UTM-like) system which has the ability to control the traffic related to that part of the airspace [8]. As one of the most important challenges for UAM is their traffic management, a great focus should be put on this matter to make it happen [13]. Automatic Dependent Surveillance-Broadcast (ADS-B) system can be a potential solution to help manage the airspace with the presence of UAM vehicles [14]. Since the ADS-B system was designed for general aviation aircraft, in order for it to be useable for UAM, there may be a need for some changes especially in the message structure [15].

1.2 Automatic Dependent Surveillance–Broadcast System

Automatic Dependent Surveillance–Broadcast (ADS–B) is a surveillance technology in which an aircraft can determine its position via satellite navigation and periodically broadcast it in order to be tracked. The information sent by the aircraft can be received by air traffic control ground stations as well as other aircraft to provide situational awareness and allow self-separation. ADS–B is automatic as no pilot or external input is required and is dependent as it depends on the data being received from the aircraft’s navigation system. ADS-B is able to replace radar in being the primary surveillance method for controlling aircraft. In the United States, ADS-B is a necessary component of the NextGen national airspace strategy for upgrading the infrastructure and operations of the aviation. ADS-B increases safety by making an aircraft visible, real time to air traffic control and to other aircraft equipped with ADS-B by transmitting position and velocity data every second.

ADS-B makes flying notably safer for the community of aviation by providing pilots with enhanced situational awareness. Pilots in an ADS-B-equipped cockpit have the ability to see, on the flight display in the cockpit, other traffic operating in the airspace. Moreover, they receive updates on temporary flight restrictions and runway closings. Aircraft equipped with ADS-B provides the air traffic controller an ability to monitor their position more accurately and reliably and other ADS-B-equipped aircraft operating in the airspace around them have the ability to identify other aircraft and avoid conflict more easily (shown in Fig. 2). ADS-B provides a more accurate report of the position of the aircraft and enables traffic controllers to guide aircraft out of crowded airspace to fly safely.

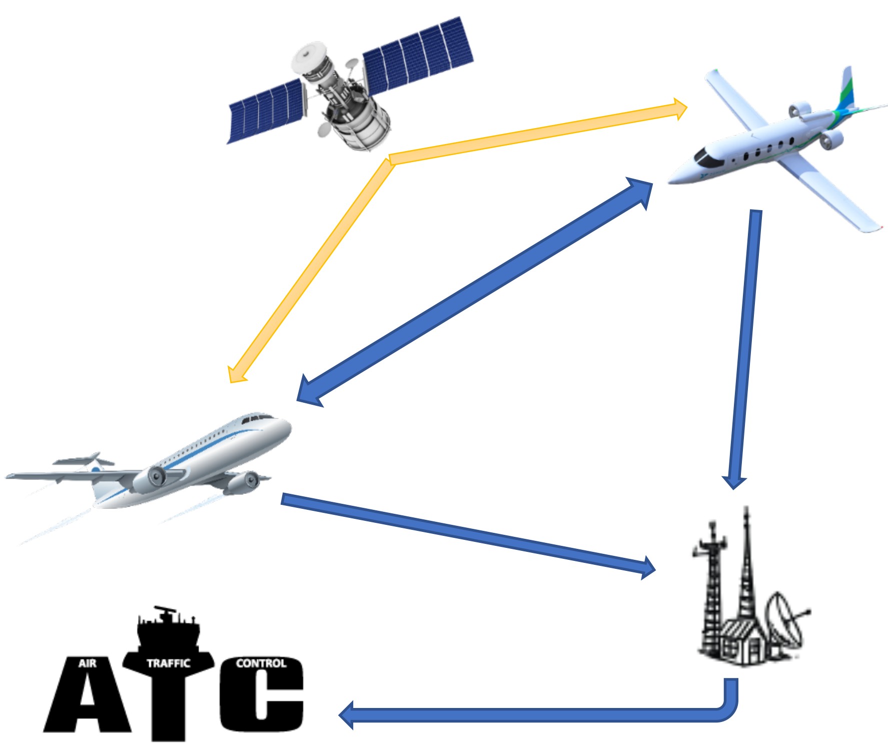


Fig. 2 Communication built through an ADS-B system

1.3 Introducing ADS-B System Usage for On-Demand Mobility Vehicles

General aviation aircraft use the ADS-B system to communicate with ATM and with other aircraft. Aircraft can use either a Mode-S system at 1090 MHz or Universal Access Transceiver (UAT) equipment at 978 MHz for ADS-B. Since the 1090 MHz frequency is so congested and most of its capacity is being used, it will be unable to accept more clients [16]. However, 978 MHz may be a possible frequency as a short or medium-term solution to be used for UAM. Since urban air mobility is a fast-growing idea, there may be a need for a new frequency to be allocated just for UAM to increase the capacity. If we consider using the UAT frequency for UAM vehicles at this stage, one of the challenges we will face is the International Civil Aviation Organization (ICAO) addressing field in the structure of the ADS-B message [17].

An ADS-B message has 112 bits of which 24 bits are allocated to the ICAO address field. For an aircraft registered in the US, the first 4 bits of the 24 bits are fixed to 1010 and the remaining 20 bits are unique for any individual aircraft [17]. These 20 bits will create 2^20 different combinations of ICAO addresses that can be allocated to each aircraft specifically. Comparing this number of different address combinations with the number of active General Aviation (GA) aircraft, which was about 224,475 in 2011 based on a report from Aircraft Owners and Pilots Association (AOPA) and has roughly remained the same till now, it can be realized that approximately 20% of the available address combinations are being used and the rest remains for future use [18]. If we consider the urban airspace with UAM vehicles everywhere, we will need a greater number of ICAO addresses to be assigned individually to each UAM vehicle.

Considering the number of active cars and trucks in the US which is about 264,000,000 and if we assume that only 1% of this number will be UAM vehicles, we will need about 2,640,000 different addresses, which exceeds the number of possible ICAO addresses (2^20) that the message structure allows to have [15]. One suggestion is to change the ADS-B message structure to increase the capacity of the ICAO address field. However, changing the structure of the ADS-B message, which has taken a long time to be prepared and fitted into airspace, does not seem to be a reasonable idea [19-20]. If we assume that only 10% of the UAM vehicles will be active at the same time, we will need 264,000 different ICAO addresses and there may be different ways to provide this number of addresses for UAM vehicles.

The first suggestion is to use the remaining addresses of GA aircraft that have been reserved for future use. As it was mentioned before, only 20% of the addresses are occupied and the remaining 80% can be used for UAM vehicles. Although this seems a straightforward solution, it may work just as a short-term solution as it has a limited number of addresses before reaching its full capacity.

The second idea is to use one of the three sets of four bits that have been reserved for future use as the first 4 bits of the ICAO address field which represents that the vehicle is flying in US airspace. These reserved sets of bits are 1011, 1101, and 1111 which will be assigned specifically to the UAM vehicles and will distinguish addresses for aircraft from UAM vehicles. By choosing one of these sets of 4 bits to be used for UAM, we will be able to open 2^20 different combinations of addresses for UAM vehicles. Even though this solution may open more vacant slots compared to the previous solution, this number is still not enough for accommodating the desired number of UAM vehicles.

The last case which seems more reasonable is to use dynamic ICAO addressing for UAM. This is very similar to Dynamic Host Configuration Protocol (DHCP) for the internet IPs which are assigned specifically to each client while requesting to connect to the network. For the case of UAM, each pilot will request an ICAO address and a preferred flight duration prior to take off.

This request will be sent to the traffic controller and a DHCP-like server with access to the pool of addresses, will randomly select an available ICAO address and send it back to the UAM vehicle. In fact, UAM vehicles will lease their address instead of owning it or, in other words, the addresses will be assigned temporarily instead of permanently assigning them to UAM vehicles. After the requested flight duration for the UAM vehicle ends, the session expires, and the address is released. The address is added back to the address pool and is ready to be reassigned to other UAM vehicles upon request. In this idea, we may use one of the reserved sets for the first 4 bits of ICAO address field to represent the UAM vehicle flying in the US airspace and that allows us to have 2^20 different combinations of ICAO addresses. An ATM-like or UTM-like system will take care of the whole process regarding the address assignment, leasing duration, and address pool control [21].

There are two major benefits for the idea of dynamic ICAO addressing for UAM. Since it is automatic, it minimizes the errors that may occur if done manually (e.g., typographical errors, configuration errors, and address conflicts) and as it is dynamic, it will allow a pool of addresses much larger than the static case.

1.4 ICAO Addressing for On-Demand Mobility Vehicles

The goal is to simulate the process of assigning an ICAO address to UAM vehicles and analyze their traffic flow. As the first step, any UAM vehicle with a known Vehicle Identification Number (VIN) that wants to start its trip, sends an address request to the traffic controller. VIN is being used to identify the UAM vehicles, but any other unique numbering system can also be used as an alternative. A section with access to the pool of addresses will oversee the address assignment to the UAM vehicle. The pool of addresses will have all the possible combinations of the 24 or 20 bits (if the first 4 bits are fixed to represent flying in the US airspace) of the ICAO address field in the ADS-B message. There is a possibility to define more fixed bits for the ICAO address field which enables defining a specific city or local area with that. Upon requesting an address, the UAM vehicle will also request a flight duration which will define the expiration time for the assigned address (shown in Fig. 3). At the end of the requested flight duration, the address expires, is added back to the pool of addresses, and will be ready to be reallocated to other UAM vehicles upon request [21-23].

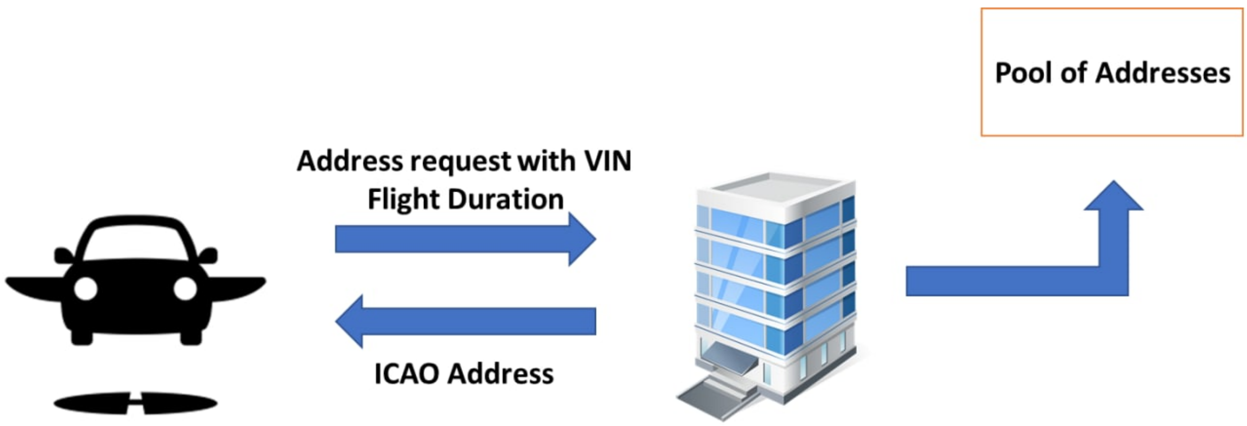


Fig. 3 ICAO addressing process for UAM vehicles

A statistical approach, based on Monte Carlo technique, has been conducted to simulate and predict the traffic flow of the UAM vehicles. A Monte Carlo simulation is a technique for understanding the uncertainty behavior in predicting models. Based on the specific assumptions, this method gives us the information around how likely the resulting outcomes are. In a Monte Carlo simulation, based on the range of estimates, a value is selected randomly for each of the tasks and based on this value the model is calculated. A typical Monte Carlo simulation repeats the model calculation for many times, using different randomly-selected values each time. After the simulation completion, a large number of results according to random input values are available. These results are used to describe how likely the various results can be reached in the model. Throughout the entire context of this paper, ODM vehicles and flying cars are all referring to UAM vehicles and these terms can be used exchangeably.

1.5 Dissertation Organization

In Chapter 2, a distribution for the number of ICAO address requests has been assumed for a typical day in a week excluding the weekends. This assumption has been made based on the time durations in a day that a city gets busier and probably at those times, there will be a greater number of requests. In order to decide on how often it is more likely and reasonable to receive ICAO address requests, the case have been simulated for four different time discretizations. The starting point for the simulation is 5:00 am. A significant increase is occurring starting in the morning through noon, a slight drop occurs at noon and then again increases through the evening. Afterwards, number of requests are being decremented showing the small number of flying cars requesting an address at those hours until beginning of the next day. As it is shown in Fig. 4, the 2-hour discretization is acting far different from the smaller duration cases and the results are getting converged for smaller durations. Obviously, for the case of 2-hour duration, the discretization is coarser, while for the smaller durations our discretization is getting finer, and the results are getting closer to each other and more reasonable in value [21].

In order to make our decision regarding the time discretization to pick for the simulation or in other words, decide on selecting the proper period that cars request an ICAO address, we need to run the simulation multiple times and check the convergence of the results. For this case, the simulation has been run for four different discretizations of 120, 60, 30, and 15 minutes in five different days. The average and median of 5 different days for each of the four durations have been compared with each other and also with the average of the average and median of the median of 5 different days and are shown in Fig. 5 and Fig. 6, respectively.

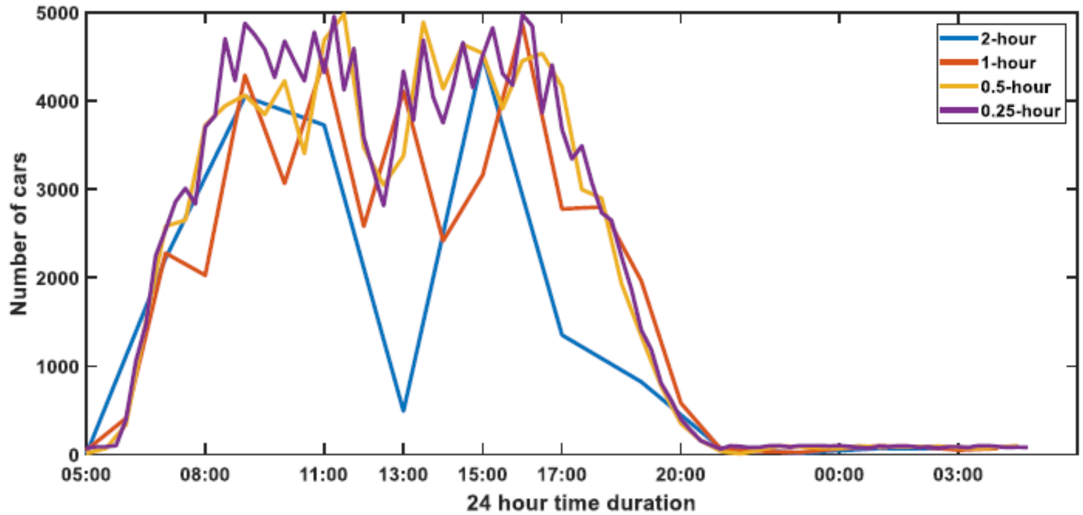


Fig. 4 Number of active cars for different time discretizations during a typical day

As it can be seen from Fig. 5 and Fig. 6, for the 2-hour duration, the values of average and median for five different days are considerably far from each other. Additionally, the values for the average and median are much smaller compared to other durations. Also, the average and median values are far different from the overall average and median. This divergence in the results means that the case of 2-hour duration cannot be an applicable choice for continuing our simulations based on that. In the next step, we focus on running the simulation based on the time duration of 1-hour. Looking at Fig. 5 and Fig. 6, a considerable improvement in the convergence of the results is recognized, but as we do not have the satisfactory convergence, still this is not the point we can select as our desired duration. Although average and median for five different days are getting high in value and closer to overall median and average line, we still have not acquired the desired point.

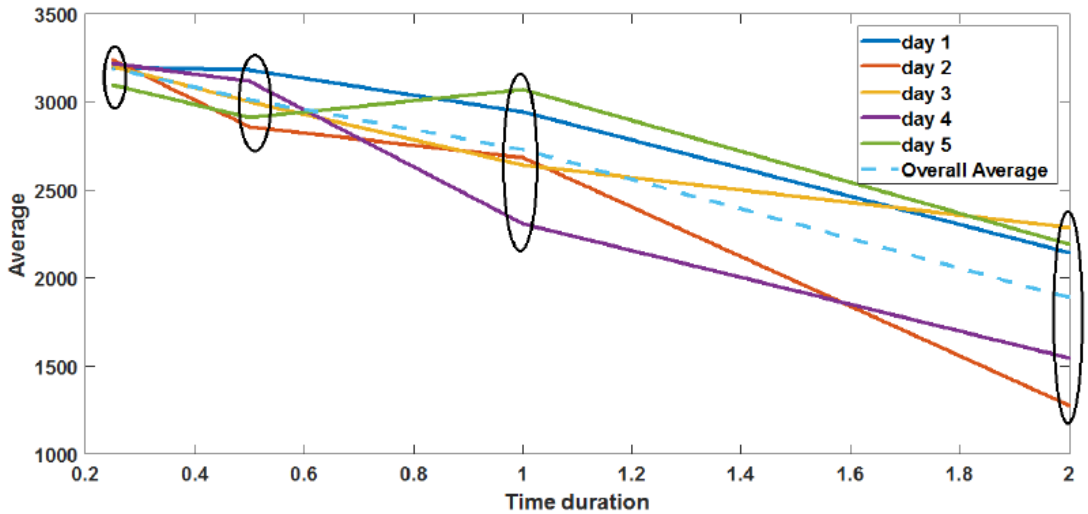


Fig. 5 Average number of cars for different time discretizations for five different days

Considering the simulation results for 30- and 15-minute time durations, a great improvement is observed as a matter of convergence. The average and median values are getting closer to the overall average and median line and the values are considerably higher in comparison to previous durations. We can conclude that based on our observations, if we make the window even smaller than 15 minutes, the data will converge more. However, making the window too small will add to the complexity of the simulated case and reduce the simulation speed. We need to make a balance between accuracy of the results and simulation time. As the considerable convergence has started from 30-minute duration and is continuing afterwards, this time duration is considered as our final decision and from this stage, the simulations will continue based on the 30-minute time discretization.

Looking at Fig. 4, by observing the line associated with the 30-minute duration, it can be noticed that the graph has two peaks, one before and one after 12:00 pm. These two peaks indicate the time when we have the highest number of active cars and the lowest number of available addresses. Analyzing the number of active cars at each duration in Fig. 1 and the average and median values of the 30-minute duration in Fig. 5 and Fig., 6 gives us a clue about the number of ICAO addresses that is needed to be allocated for a city with approximate known number of cars. This number should be chosen wisely as the important part is to be able to meet the demand of the address requests as much as possible throughout the day. Along with this, a study should be done on how the high demand in busier times of the day can be controlled. Furthermore, in order for the traffic controllers of different areas to be connected and have access to a central data where all the information of the flights in all regions are stored, a central traffic management system or a central controller is needed.

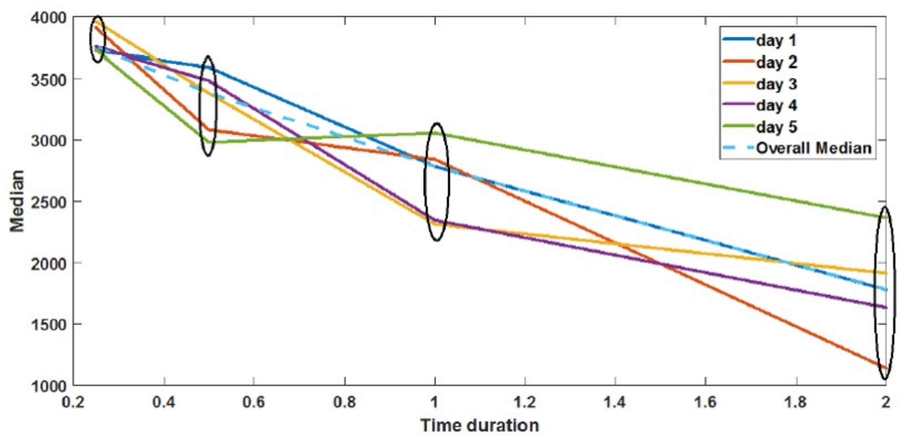


Fig. 6 Median of the number of cars for different time discretizations for five different days

Chapter 2 attempts to layout a vision for an issue related to a new air transportation system. Some suggestions have been made and the most reasonable one is picked for further investigation and simulations. Then, a picture of assigning an ICAO address to a car and getting it back is explained and related simulations are conducted to figure out the behavior in a typical day considering the number of cars requesting an address with different time discretizations. After monitoring the behavior of four different time durations, one of them is selected to be followed in future simulations.

In Chapter 3, the simulations are conducted for an assumed city with 5000 number of registered flying cars and the observation window for examining the traffic flow will be 30 minutes. In the first step, the simulation is conducted for the case which allows the flying cars to request one of the 1 hour, 1.5 hours, 2 hours, 2.5 hours, 3 hours, or 5 hours of flight durations. We have made an assumption for the percentage of cars requesting specific flight durations throughout the day and the pattern for the traffic flow as well. However, any other assumptions or a data from a real case would also work. Running the analysis tool for this case, the Monte Carlo-based simulation result is as illustrated in Fig. 7.

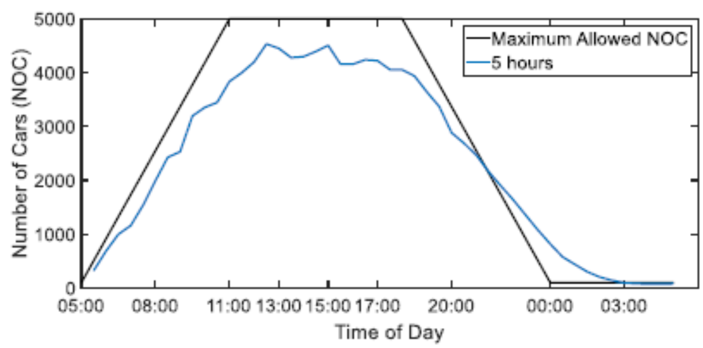


Fig. 7 Number of active cars throughout 24 hours

The black line shown in Fig. 7 is the pattern that has been assumed for the maximum number of cars allowed to be active throughout the day and the blue line is representing the number of active cars while allowing them to request the maximum flight duration of 5 hours. As it can be seen, at the busy period of the day, which is considered from 11:00 am to 6:00 pm, the number of active cars is very close to 5000 which is the total number of registered flying cars in the city. In order to figure out how many addresses should be allocated to the city, the average number of active cars throughout the busy period of the day has been analyzed and the results are presented in Fig. 8.

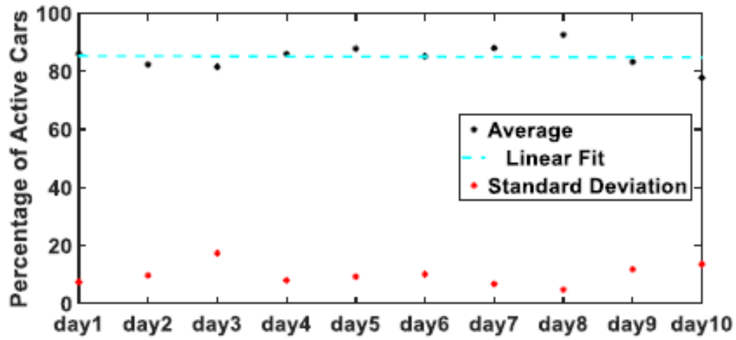


Fig. 8 Percentage of active cars for 10 typical days

As it is shown in Fig. 8, in average, about 85% of the cars are active during the busy period and consequently, 85% of the ICAO addresses will be occupied in average. However, in order to decide on the number of addresses needed to accommodate the most efficient number of cars, one possible way is to make the decision based on both the average and the standard deviation. As discussed in previous sections, the major issue with the addressing of the ODM vehicles is the limitation of the available number of addresses. Therefore, at this stage, it is important that instead of allocating the same number of ICAO addresses as the number of registered cars in the city, we find out the most efficient number which accommodates the possible maximum number of flying cars. In order to observe the effect of allowed flight durations on the traffic flow throughout the day, the maximum allowed flight duration is decreased from 5 hours to 3 hours and the same simulations have been conducted [22-23]. The simulation results are shown in Fig. 9 and Fig. 10.

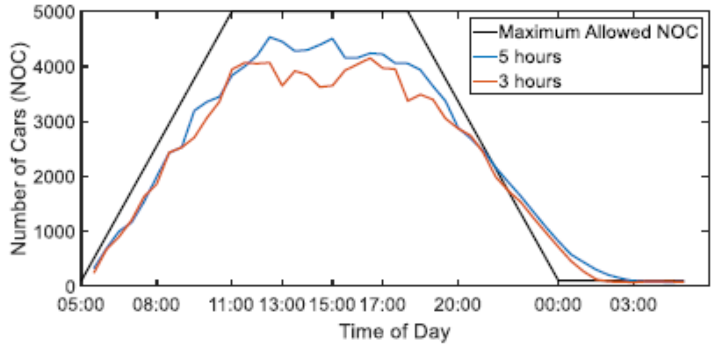


Fig. 9 Number of active cars throughout 24 hours

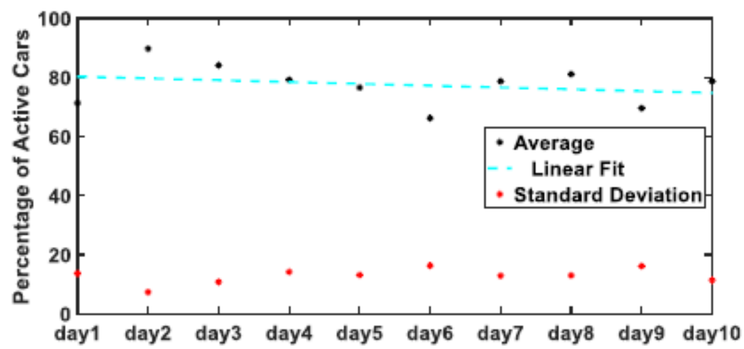


Fig. 10 Percentage of active cars for 10 typical days

Fig. 9 is illustrating the cases of maximum allowed flight durations of 5 hours and 3 hours. As it is demonstrated, the number of active cars has decreased in busy period of the day because of the decrement in the maximum flight duration. In order to prove this, the average number of active cars, which shows the average of the addresses needed, has been presented in Fig. 10. Comparing the percentage for the average active cars for the 5 hours and 3 hours cases, the number has decreased from 85% to about 75%-80% and this shows that decreasing the maximum allowed flight duration in busy periods will help to reduce the number of addresses needed to accommodate the sufficient number of cars. The reduction from more than 85% to 75%-80% when decreasing the allowed flight times, was a reason to conduct the simulations for the case of maximum flight duration of 2 hours and study the effect of that on the number of addresses needed. The associated simulation results have been presented in Fig. 11 and Fig. 12.

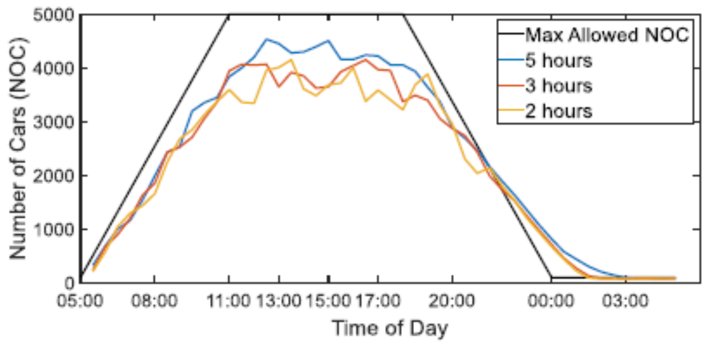


Fig. 11 Number of active cars throughout 24 hours

Comparing the results of reducing the maximum flight duration to 2 hours with the previous cases of maximum allowed durations of 5 and 3 hours, as displayed in Fig. 11, the number of active cars has decreased. Furthermore, Fig. 12 is representing the average number of cars throughout 10 typical days and the average has stayed roughly at 72%, which in comparison to the previous cases will end up with fewer number of addresses needed. Limiting the maximum allowed flight time in the busy period results in the reduction of the number of addresses needed to be allocated to a city, but this limitation can be applied depending on the situation and the demand. This limitation will help the traffic management to be able to accommodate a greater number of address requests.

After examining 3 different cases and studying the effect of decreasing the maximum allowed flight duration, a special case is introduced where the only available flight duration to be requested is one hour. Due to the current battery limitations, this special case is studied for the situations such as last mile deliveries which may be a point of interest for some companies. In this case all of the address requests will be assigned an ICAO address for one hour and when the time ends, the address will be expired. The generated simulation results for this particular case have been shown in Fig. 13 and Fig. 14.

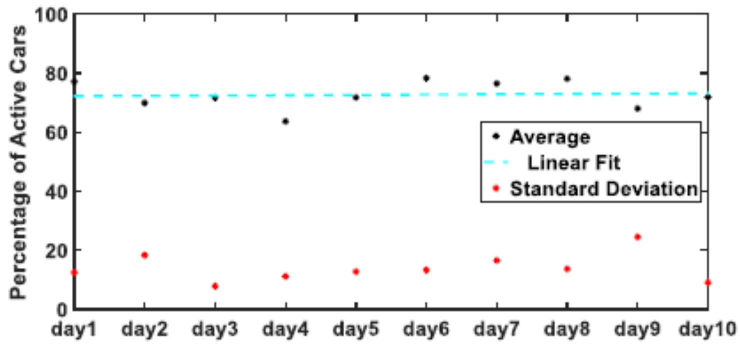


Fig. 12 Percentage of active cars for 10 typical days

As displayed in Fig. 13, the average number of active cars and consequently, the average number of addresses needed, have been decreased in comparison to the previous cases. As shown in Fig. 14, the average number of addresses needed has decreased from about more than 85% to less than 65% which proves that decreasing the maximum allowed flight duration based on the situation will decrease the number of addresses needed. The comparison between all four cases is shown in Fig. 15.

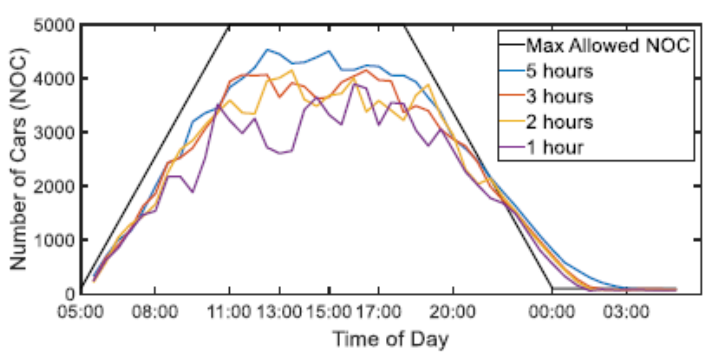


Fig. 13 Number of active cars throughout 24 hours

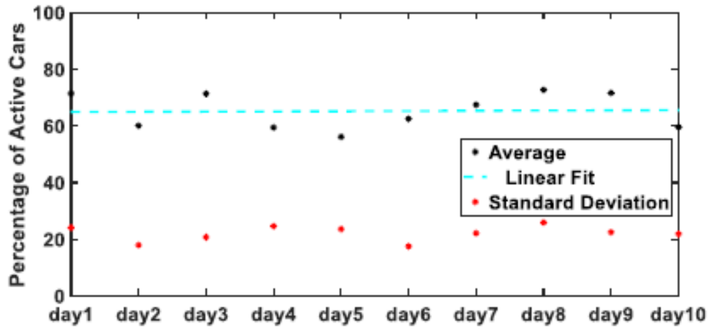


Fig. 14 Percentage of active cars for 10 typical days

Fig. 15 illustrates the difference in percentage of active cars for different time limitations and different number of days for which the simulation is conducted. This graph brings the results of the studied four cases together to make the comparison much easier. As shown in Fig. 15, the average number of addresses needed to be allocated to a city with known registered number of cars will decrease by decreasing the maximum flight duration allowed to be requested in busy periods of the day. The average of the address requests or in other words, the average percentage of active cars, is significantly decreasing when reducing the allowed flight time and this will help use the addresses more efficiently and accommodate as much flying cars as possible.

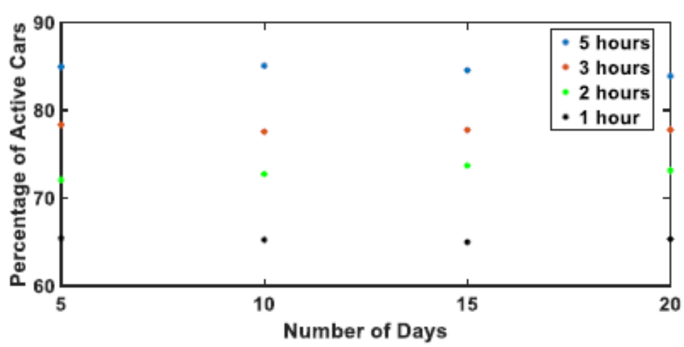


Fig. 15 Percentage of active cars for different number of days and different maximum allowed flight durations

Furthermore, in Chapter 3, effect of different policies and flexibilities on the traffic flow patterns are observed. First scenario is observing the effect of price assignment to the flight durations where the longer flight durations will be assigned higher prices on the traffic flow in high demand periods. The simulation results associated with the case of maximum allowed flight duration of 5 hours and the case that price adjustment is applied are shown in Fig. 16. The black line presented in the figure is the considered pattern for the maximum allowed number of active cars or, in other words, the assumed traffic flow, throughout the day and the blue line is associated with the case where the maximum allowed flight duration that can be requested is 5 hours with no price adjustments.

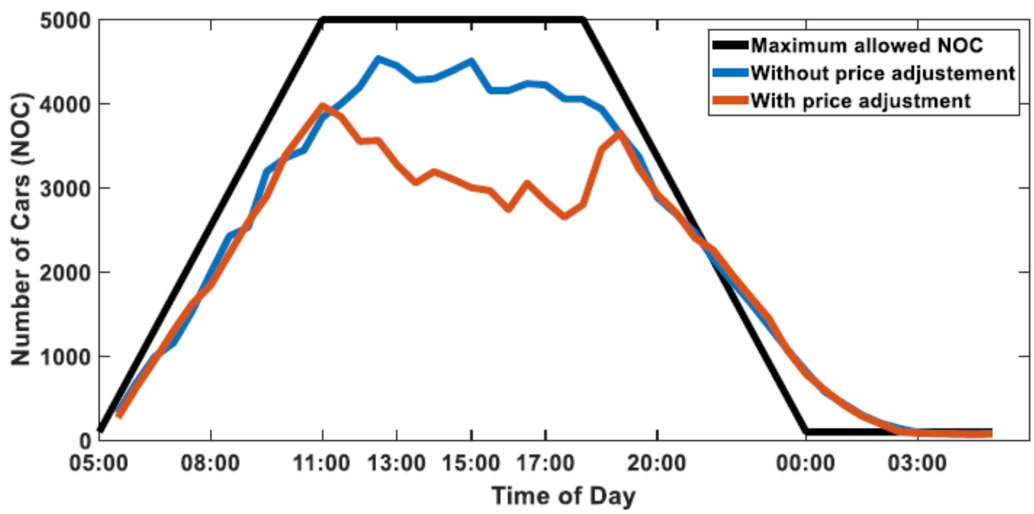


Fig. 16 Number of active cars throughout 24 hours. (Maximum allowed flight duration is 5 hours)

The red line shown in Fig. 16 is representing the traffic flow for the case that the price adjustment has been applied for the busy period of the day which is considered from 11:00 am to 6:00 pm. As depicted, the number of active cars in the busy period of the case without any price adjustments is considerably more compared with the case with the price adjustment. In order to observe the average number of active cars more accurately and, consequently, the number of ICAO addresses needed for the case with the price adjustment, a simulation has been conducted and the results are shown in Fig. 17.

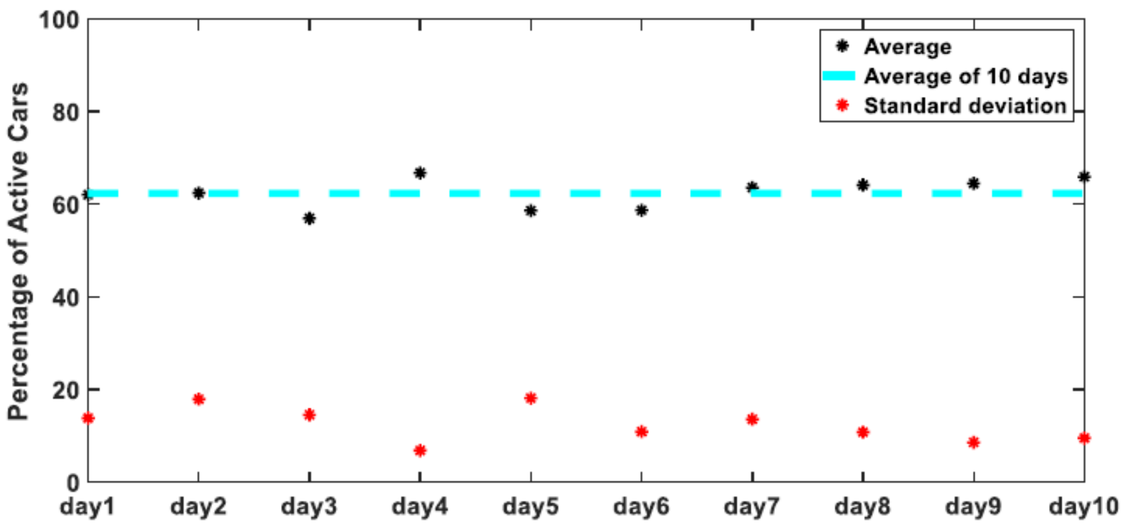


Fig. 17 Percentage of active cars for 10 typical days. (With price adjustment)

As illustrated in Fig. 17, the average number of active cars in the busy period of this case is about 60% and notably lower than the case without price adjustment which is roughly 85% based on the conducted simulations. However, in order to make an appropriate decision on the number of ICAO addresses associated with each different case, considering both the average and the standard deviation would lead to a more accurate decision. Based on what has been shown in Fig. 16 and Fig. 17, it is proved that assigning higher prices to longer flight durations will help to alleviate the traffic in higher demand periods.

The second scenario observed is the situation that a certain percentage of denials can be tolerated. In this suggested case, a tolerable percentage of requests made in the busy period will be denied by the traffic control section and the impact of this scenario is observed on the traffic flow in high demand periods. The reason that it is named as a static method is that the clients that their requests are denied need to go through the requesting process once again any time after their request is denied. For the conducted simulation in this section, it is assumed that denying 20% of the requests during the busy period can be tolerated. However, the analysis tool is independent of this number and may be scaled in different situations. The simulation results associated with this case are shown in Fig. 18 and Fig. 19.

As depicted in Fig. 18, the red line, which is associated with the case of denying 20% of the requests in the high-demand period, stays less than the case without any denials. Fig. 19 illustrates the average number of active cars in the busy period and consequently the number of addresses needed for this case. The average number of active cars is decreased from 85% to roughly 75%, which represents the effect of denying a certain percentage of cars on the traffic flow. As already discussed, the number of addresses that can be allocated to each area with a known number of registered flying cars is limited and observing the traffic flow for different cases will inform us about how each scenario affects the results.

The third scenario introduced and observed is a case similar to the previous one where a certain percentage of requests can be denied during high-demand periods without any significant inconveniences to customers. In this case, however, the requests will be denied dynamically instead of statically. In this study, the dynamic denial is defined as follows: the denied requests, due to the address unavailability, will be waitlisted and assigned an address as soon it becomes available based on a first come first served basis. This is very similar to a call being on hold instead of being completely rejected. Unlike the static denial concept where the controller is not responsible for the denied requests, when requests are dynamically denied, they will be entered in a queue and assigned an address when available. The simulation results for the dynamic denial case are shown in Fig. 20 and Fig. 21.

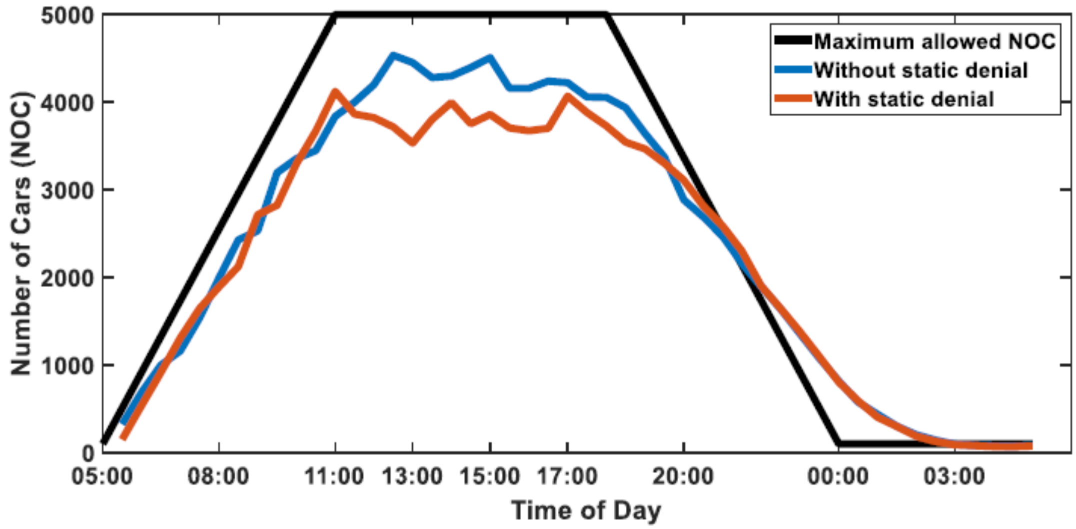


Fig. 18 Number of active cars throughout 24 hours. (Maximum allowed flight duration is 5 hours)

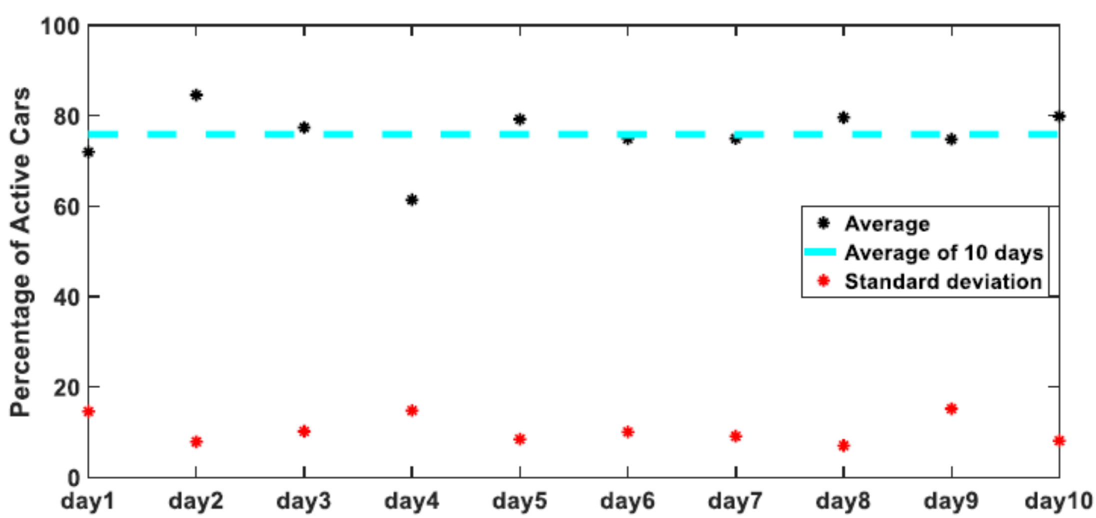
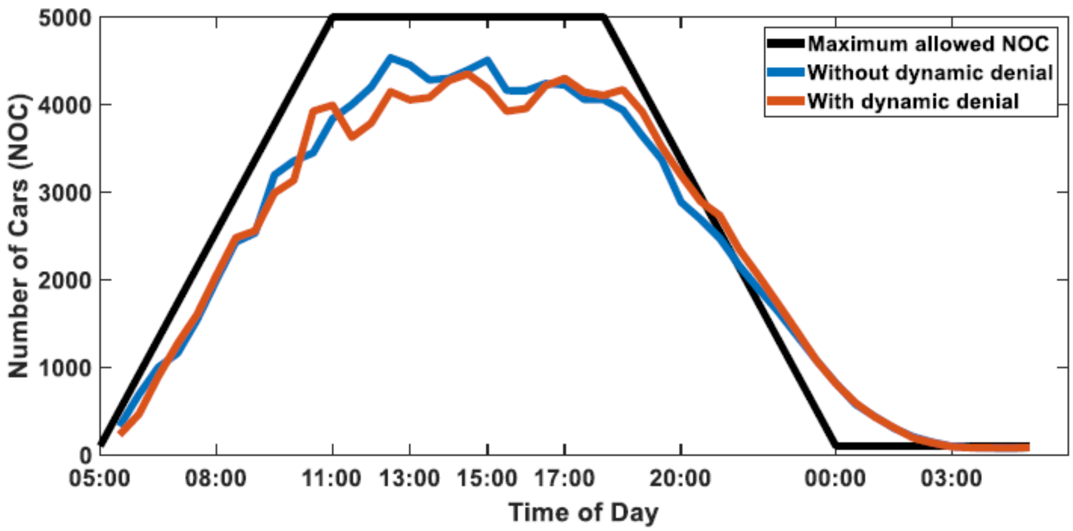


Fig. 19 Percentage of active cars for 10 typical days. (With static denial)

Comparing Fig. 18 and Fig. 20 which are associated with the cases of static and dynamic denials respectively, it can be seen that although the traffic flow for the dynamic denial case in Fig. 20 in high demand period stays less than the case without denials, it is slightly more than the static case. The reason lies behind the fact that in the dynamic denial case unlike the static one, the requests are not completely denied, but are on hold instead and will be given an address whenever available.



.

Fig. 20 Number of active cars throughout 24 hours. (Maximum allowed flight duration is 5 hours)

As depicted in Fig. 21, the average percentage of active cars has decreased relative to the case without any denials from about 85% of the whole registered cars to 80%, but this decrement is less than the decrease in the percentage of active cars for the static case. By comparing the results from the dynamic and static denial cases, it can be concluded that each of the static and dynamic cases has its own benefits and can be applied based on the situation. The static denial alleviates the traffic flow faster, but completely rejects the requests with no wait-listing option. On the other hand, the dynamic denial has a slight decrease for the same denial percentage but provides the option for the requests to be waitlisted until an address is available to be assigned. Each of these suggested scenarios can either be applied as independent policies or be combined and create a new policy which can be applied to alleviate the traffic flow to make traffic management much easier. In Chapter 4, three different scenarios are introduced to observe the cases where the UAM vehicles (Shown in Fig. 22) are able to make both inter-city and intra-city trips. The developed analysis tool using the Monte-Carlo simulation technique predicts the results and the outcomes of the three scenarios and Chapter 5 summarizes the research done in this work.

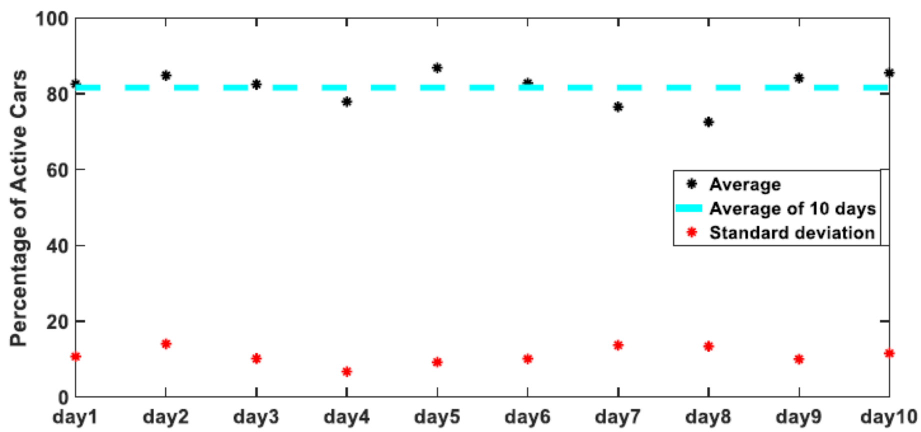


Fig. 21 Percentage of active cars for 10 typical days. (With dynamic denial)

Fig. 22 A UAM vehicle while landing (From cheskyw/123RF)

1.6 References

[1] Holden, J., and Goel, N., "Fast-Forwarding to a Future of On-Demand, Urban Air Transportation," Uber Elevate, Uber White Paper, San Francisco, CA, Oct. 2016.

[2] Moore, M., Goodrich, K., Viken, J., Smith, J., Fredericks, B., Trani, T., Barraclough, J., German, B., and Patterson, M., "High Speed Mobility through On-Demand Aviation," Aviation Technology, Integration, and Operations Conference, AIAA Paper 2013-4373, 2013.
https://doi.org/10.2514/6.2013-4373

[3] Mueller, E., Kopardekar, P., and Goodrich, K., "Enabling Airspace Integration for High Density On-Demand Mobility Operations," 17th AIAA Aviation Technology, Integration, and Operations Conference, AIAA Aviation Forum, AIAA Paper 2017-3086, 2017.
https://doi.org/10.2514/6.2017-3086

[4] Moore, M., "Concept of Operations for Highly Autonomous Electric Zip Aviation," 12th Aviation Technology, Integration and Operations (ATIO) Conference, AIAA Paper 2012-5472, 2012.
https://doi.org/10.2514/6.2012-5472

[5] Patterson, M., German, B., and Moore, M., "Performance Analysis and Design of On Demand Electric Aircraft Concepts," 12th Aviation Technology, Integration and Operations (ATIO) Conference, AIAA Paper 2012-5474, 2012.
https://doi.org/10.2514/6.2012-5474

[6] Smith, J., Viken, J., Guerreiro, N., Dollyhigh, S., Fenbert, J., Hartman, C., Kwa, T., and Moore, M., "Projected Demand and Potential Impacts to the National Airspace System of Autonomous, Electric, On-Demand Small Aircraft," 12th Aviation Technology, Integration and Operations (ATIO) Conference, AIAA Paper 2012-5595, 2012.
https://doi.org/10.2514/6.2012-5595

[7] Vascik, P. D., and Hansman, R. J., "Systems-Level Analysis of on Demand Mobility for Aviation," International Center for Air Transportation (ICAT) Rept. ICAT-2017-02, Massachusetts Institute of Technology, Cambridge, MA, Feb. 2017.

[8] Kopardekar, P., Rios, J., Prevot, T., Johnson, M., Jung, J., and Robinson, J, "Unmanned Aircraft System Traffic Management (UTM) Concept of Operations," Aviation Technology, Integration and Operations Conference, AIAA Paper 2016-3292, 2016.
https://doi.org/10.2514/6.2016-3292

[9] Rorie, R. C., Fern, L., and Shively, R. J., "The Impact of Suggestive Maneuver Guidance on UAS Pilots Performing the Detect and Avoid Function," Infotech@Aerospace, AIAA Paper 2016-1002, 2016.
https://doi.org/10.2514/6.2016-1002

[10] Rorie, R. C., Fern, L., Roberts, Z., Monk, K., Santiago, C., and Shively, R. J., "Validation of Minimum Display Requirements for a UAS Detect and Avoid System," Aviation Technology, Integration, and Operations Conference, AIAA Paper 2017-4483, 2017.
https://doi.org/10.2514/6.2017-4483

[11] Jang, D. S., Ippolito, C., Sankararaman, S., and Stepanyan, V., "Concepts of Airspace Structures and System Analysis for UAS Traffic Flows for Urban Areas," Infotech@Aerospace, AIAA Paper 2017-0449, 2017.
https://doi.org/10.2514/6.2017-0449

[12] Salleh, M., Tan, D. Y., Koh, C. H., and Low, K. H., "Preliminary Concept of Operations (ConOps) for Traffic Management of Unmanned Aircraft Systems (TM-UAS) in Urban Environment," Infotech@Aerospace, AIAA Paper 2017-0223, 2017.
https://doi.org/10.2514/6.2017-0223

[13] Holmes, B., Parker, R., Stanley, D., McHugh, P., Garrow, L., Masson, P., and Olcott, J., "NASA Strategic Framework for On-Demand Air Mobility," NASA NNL13AA08B, Hampton, VA, Jan. 2017.

[14] Duan, P., and Rankin, J., "ADS-B Feasibility Study for Commercial Space Flight Operations," 29th Digital Avionics Systems Conference, IEEE Publ., Piscataway, NJ, 2010, pp. 3.A.1-1–3.A.1-11.
https://doi.org/10.1109/DASC.2010.5655472

[15] Duan, P., and Rankin, J., "ADS-B Space-Oriented Message Set Design," 2011 Integrated Communications, Navigation, and Surveillance Conference Proceedings, IEEE Publ., Piscataway, NJ, 2011, pp. O2-1–O2-12.
https://doi.org/10.1109/ICNSURV.2011.5935353

[16] Leiden, K., Kopardekar, P., and Green, S., "Controller Workload Analysis Methodology to Predict Increases in Airspace Capacity," Aviation Technology, Integration, and Operations Conference, AIAA Paper 2003-6808, 2003.
https://doi.org/10.2514/6.2003-6808

[17] International Civil Aviation Organization, "Registration of Aircraft Addresses with Mode S Transponders," Third Meeting of North American, Central American and Caribbean Directors of Civil Aviation (NACC/DCA/3 - WP/05), Montreal, Canada, Sept. 2008.

[18] https://www.aopa.org/about/general-aviation-statistics/active-general-aviationaircraft- in the-u-s [retrieved 16 July 2020].

[19] Erzberger, H., "Transforming the NAS: The Next Generation Air Traffic Control System," NASA TP-2004-212828, Oct. 2004.

[20] Gawdiak, Y., Holmes, B., Sawhill, B., Herriot, J., Ballard, D., Eckhause, J., Long, D., Hemm, R., Creedon, J., Murphy, C., Thompson, T., Wieland, F., Price, G., Marcolini, M., Moore, M., and

Alcabin, M., “Air Transportation Strategic Trade Space Modeling and Assessment Through Analysis of On-Demand Air Mobility with Electric Aircraft,” Aviation Technology, Integration, and Operations Conference, AIAA Paper 2012-5594, 2012.
https://doi.org/10.2514/6.2012-5594

[21] Ghayouraneh, S., El-Ghazaly, S., and Rankin, J., “Dynamic Addressing for On-Demand Mobility,” 2018 Aviation Technology, Integration, and Operations Conference, AIAA Aviation Forum, AIAA Paper 2018-4152, 2018.
https://doi.org/10.2514/6.2018-4152

[22] Ghayouraneh, S., Rankin, J. M., and El-Ghazaly, S. M., “Practical Considerations in Traffic Flow Systems for ODM Vehicles,” 2019 Integrated Communications, Navigation and Surveillance Conference (ICNS), IEEE Publ., Piscataway, NJ, 2019, pp. 1–7.
https://doi.org/10.1109/ICNSURV.2019.8735402

[23] Ghayouraneh, S., El-Ghazaly, S. M., and Rankin, J. M., “Investigation of Traffic Flow for ODM Vehicles in Dynamic ICAO Addressing Process,” AIAA Aviation Forum, AIAA Paper 2019-3627, 2019.
https://doi.org/10.2514/6.2019-3627

Chapter 2

Dynamic Addressing for Urban Air Mobility Vehicles

Authors: Sara Ghayouraneh, James M. Rankin, Samir M. El-Ghazaly

2.1 Introduction

As the population grows, especially in larger cities, people waste a great amount of their day in heavy traffic and there is always a struggle to find different ways to reduce this. People in San Francisco are wasting an average of 230 hours per year in traffic going to work and coming back home and this means losing half a million hours of productivity per day. This wasted time increases to seven weeks per year for people in Los Angeles. The huge amount of commute time causes a high level of fuel consumption and air pollution, spending less time with family, having less time at work which affects the economic growth, and a high level of stress [1]. Although much has been done to help make the traffic lighter, population growth and people's preference to use their personal cars are making the megacities more crowded each day. Therefore, the idea of Urban Air Mobility (UAM) or On-Demand Mobility (ODM) is introduced to be a potential solution for traffic congestion [2]. Based on this idea, air transportation and UAM vehicles will be involved in a part of an urban transportation system and can be an efficient and quiet way of transportation [3]. Studies have shown that a commute time of two hours from San Jose to San Francisco can be reduced to 15 minutes with these UAM vehicles [1].

Previously, it has been talked about the importance of on-demand urban air transportation and various critical challenges that will appear while moving forward through the future urban transportation in the air. These challenges, which are considered from both design and air traffic management perspectives, have been explained in full details and some possible solutions suggested. Furthermore, a broad view as a starting point to think about the path to urban air-transportation systems and flying cars has been given [1]. The concept of ZIP Aviation which enables new markets for aviation and creates more flexibility than the other ways of transportation has been introduced. This importance of electric propulsion and autonomy [4] which offer a chance to provide new high speed and On-demand transportation alternatives which can eliminate the huge costs needed to be invested in ground-based infrastructure has been discussed [2]. The concept of ODM along with some technical improvements such as enhancing the circuitries and thermal management for the batteries associated with airspace integration has been highlighted [4-7]. Furthermore, various approaches regarding enabling the existing system to support the ODM-related traffic management system have been discussed [3]. Moreover, a broad view of the predicted ODM services has been given to indicate operational restrictions and examine the short and long-term alleviation opportunities. Policy and legal challenges regarding the acceptance of community, impacts on the environment, and flying in lower altitudes have also been discussed [8].

Currently, the structure and design of the airspace defined by Federal Aviation Administration (FAA) do not have enough flexibility to allow a new air transportation system as ODM and a great effort is needed to allocate the airspace to different air transportation systems [8]. Nowadays, Unmanned Aerial Systems (UAS) are flying at an altitude range of below 400 feet where few, if any, manned aircraft are flying. With Unmanned Traffic Management (UTM) and Detect and Avoid systems (DAA), UAS are able to communicate with each other with a minimum collision risk [9-12]. However, On-demand mobility vehicles are expected to fly at the range of 1000 - 3000 feet which, requires the UAM vehicles to communicate among themselves and with other aviation-related vehicles flying in that range [3]. Since UAM is recognized as a manned transportation, there will be a higher risk of collision compared to unmanned vehicles and therefore, there is a need for an Air Traffic Management-like (ATM-like) or Unmanned Traffic Management-like (UTM-like) system which has the ability to control the traffic related to that part of the airspace [12]. As one of the most important challenges for ODM is their traffic management, a great focus should be put on this matter to make it happen [13]. Automatic Dependent Surveillance-Broadcast (ADS-B) system can be a potential solution to help in managing the airspace with the presence of flying cars [14]. Since the ADS-B system was designed for general aviation aircraft, in order to be useable for UAM, there may be a need for some changes especially in the message structure [15].

In the next section, a brief explanation of the ADS-B system and the usage of it for flying cars will be discussed. Then, some challenges regarding the message structure are mentioned and some solutions provided. Later, the simulation part is done in two different sections for two different cases. The first case is done based on specific assumptions and the second one is for real data. The results from the first case will be used in the simulations of the second one.

2.2 ADS-B for Urban Air Mobility Vehicles

General aviation aircraft use the ADS-B system to communicate with ATM and with other aircraft. Aircraft can use either a Mode-S system at 1090 MHz or Universal Access Transceiver (UAT) equipment at 978 MHz for ADS-B. Since the 1090 MHz frequency is so congested and most of its capacity is being used, it will be unable to accept more clients [16]. However, 978 MHz may be a possible frequency as a short or medium-term solution to be used for UAM. Since Urban Air Mobility is a fast-growing idea, there may be a need for a new frequency to be allocated just for UAM to increase the capacity. If we consider using the UAT frequency for flying cars at this stage, one of the challenges we will face is the International Civil Aviation Organization (ICAO) addressing field in the structure of the ADS-B message [17].

An ADS-B message has 112 bits of which 24 bits are allocated to the ICAO address field. For an aircraft registered in the US, the first 4 bits of the 24 bits are fixed to 1010 and the remaining 20 bits are unique for any individual aircraft [17]. These 20 bits will create 2^20 different combinations of ICAO addresses that can be allocated to each aircraft specifically. Comparing this number of different address combinations with the number of active General Aviation (GA) aircraft, which was about 224,475 in 2011 based on a report from Aircraft Owners and Pilots Association (AOPA) and has roughly remained the same till now, it can be realized that approximately 20% of the available address combinations are being used and the rest remain for future use. If we consider the urban airspace with UAM vehicles everywhere, we will need a greater number of ICAO addresses to be assigned individually to each UAM vehicle.

Considering the number of active cars and trucks in the US which is about 264,000,000 and if we assume that only 1% of this number will be UAM vehicles, we will need about 2,640,000 different addresses, which exceeds the number of possible ICAO addresses (2^20) that the message structure allows us to have [18]. One suggestion is to change the ADS-B message structure to increase the capacity of the ICAO address field. However, changing the structure of the ADS-B message which has taken a long time to be prepared and fitted into airspace does not seem a reasonable idea [19-20]. If we assume that only 10% of the UAM vehicles will be active at the same time, we will need 264,000 different ICAO addresses and there may be different ways to provide this number of addresses for UAM vehicles. Some of the possible ways are addressed below [21-23]:

The first suggestion is to use the remaining addresses of GA aircraft that have been reserved for future use. As it was mentioned before, only 20% of the addresses are occupied and the remaining 80% can be used for UAM vehicles. Although this seems a straightforward solution, it may work just as a short-term solution as it has a limited number of addresses before reaching its full capacity.

Second is to use one of the three sets of four bits that have been reserved for future use as the first 4 bits of the ICAO address field which represents that the vehicle is flying in US airspace. These reserved sets of bits are 1011, 1101, and 1111 which will be assigned specifically to the UAM vehicles and will distinguish addresses for aircraft from UAM vehicles. By choosing one of these sets of 4 bits to be used for UAM, we will be able to open 2^20 different combination of addresses for UAM vehicles. Even though this solution may open more vacant slots compared to the previous solution, this number is still not enough for accommodating the desired number of flying cars.

The last case which seems more reasonable is to use dynamic ICAO addressing for UAM. This is very similar to Dynamic Host Configuration Protocol (DHCP) for the internet IPs which are assigned specifically to each client while requesting to connect to the network. For the case of UAM, each pilot will request an ICAO address and a preferred flight duration prior to take off. This request will be sent to the traffic controller and a DHCP-like server with access to the pool of addresses, will randomly select an available ICAO address and send it back to the car. In fact, UAM vehicles will lease their address instead of owning it or in other words, the addresses will be assigned temporarily instead of permanently assigning them to the UAM vehicles. After the requested flight duration for the UAM vehicle ends, the session expires, and the address is released. The address is added back to the address pool and is ready to be reassigned to other UAM vehicles upon request. In this idea, one of the reserved sets for the first 4 bits of ICAO address field to represent the car flying in the US airspace and that allows to have 2^20 different combinations of ICAO addresses may be used. An ATM-like or UTM-like system will take care of the whole process regarding the address assignment, leasing duration, and address pool control.

There are two major benefits for the idea of dynamic ICAO addressing for UAM. Since it is automatic, it minimizes the errors that may occur if done manually (e.g., typographical errors, configuration errors, and address conflicts) and as it is dynamic, it will allow a pool of addresses much larger than the static case.

2.3 ICAO Addressing for UAM Vehicles

In this section, the goal is to simulate the process of assigning an ICAO address to UAM vehicles. As the first step, any UAM vehicle with a known Vehicle Identification Number (VIN) that wants to start its trip, sends an address request to the traffic controller. VIN is being used to identify the UAM vehicles, but any other unique numbering system can also be used as an alternative. A section with access to the pool of addresses will oversee the address assignment to the UAM vehicle. The pool of addresses will have all the possible combinations of the 24 or 20 bits (if the first 4 bits are fixed to represent flying in the US airspace) of the ICAO address field in the ADS-B message. There is a possibility to define more fixed bits for the ICAO address field which enables defining a specific city or local area with that. Upon requesting an address, the UAM vehicle will also request a flight duration which will define the expiration time for the assigned address. At the end of the requested flight duration, the address expires, added back to the pool of addresses, and ready to be reallocated to other UAM vehicles upon request [21-23].

A statistical approach, based on the Monte Carlo technique, has been conducted to simulate the desired case. A Monte Carlo simulation is a technique for understanding the uncertainty behavior in predicting models. Based on the specific assumptions, this method gives us the information around how likely the resulting outcomes are. In a Monte Carlo simulation, based on the range of estimates, a value is selected randomly for each of the tasks and based on this value the model is calculated. A typical Monte Carlo simulation repeats the model calculation for many times, using different randomly-selected values each time. After the simulation completion, a large number of results according to random input values are available. These results are used to describe how likely the various results can be reached in the model.

To simulate the process and study the traffic flow, an analysis tool has been developed. A city with a number of 5000 registered UAM vehicles is assumed and the distribution of the number of active UAM vehicles throughout the 24 hours of the day has been studied. Although an assumption has been made regarding the number of registered UAM vehicles in that specific city, the tool is totally independent of the number of UAM vehicles and can be scaled up/down when needed. The analysis tool has been developed in MATLAB, and the simulation results have been analyzed in the next section. The assumptions and associated simulation results will be discussed in two sections as two different cases. In the first section, simulations have been done based on some assumptions and at the end, the discussion will be concluded with a decision that we will be using in the second section. Later, simulations based on some real data will be conducted and the associated results will be discussed.

2.4 Analysis Scenarios

At this stage, the Monte Carlo simulations have been run based on the two assumed patterns. The start time for our simulations is considered 5:00 am. The first assumption has been made for the pattern of the expected demand profile of the ICAO address requests throughout the day. This pattern is shown in Fig. 1. The second assumption, presented in Fig. 2, displays the percentage of the UAM vehicles requesting an ICAO address during a day versus their requested flight duration. As it is shown in Fig. 1, based on what it has been assumed, the number of requests increases until reaching its maximum value, then it stays steady through noon, experiences a slight drop, and continues at its maximum till evening. Then, the number of requests will stay steady at its minimum until the next day.

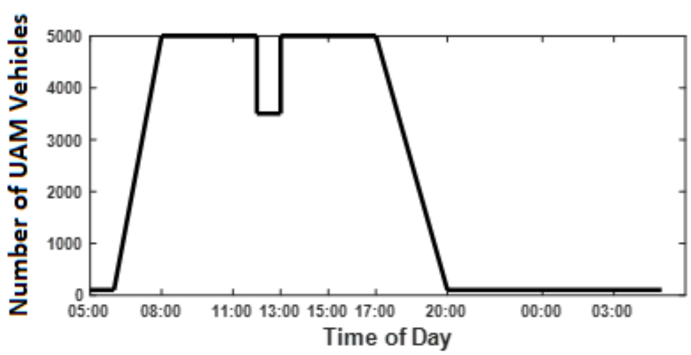


Fig. 1 Expected demand profile of the ICAO address requests throughout 24 hours.

To see the distribution of the UAM vehicles requesting an address throughout 24 hours of the day, the 24 hours of the day has been discretized to smaller time windows and the number of UAM vehicles at each window is observed. For running the simulation, 4 different observation windows of 2-hour, 1-hour, 30- and 15-minute durations were considered to decide on how often the address requests will be received. This is done to find out the best choice of observation window for running our simulations. As it is presented in the figure below, starting from 5:00 am, the number of active UAM vehicles is increasing, staying at its maximum and then decreasing through evening hours to stay at its minimum until the next day. It is clear from Fig. 3 that the result of the simulation for 2-hour observation window acts much different from the other observation windows. In general, the results are getting converged while the observation windows are made smaller. This is because, for the case of 2-hour observation window, the discretization is coarser, but moving forward to smaller windows, the discretization is getting finer, and the results are getting converged.

To decide on which observation window to pick for future simulations, the convergence of the results should be compared for multiple simulation runs. To do this, the simulation has been run for five typical days of a week excluding weekends and for four different observation windows. The daily average for the number of active UAM vehicles has been derived for five typical days and the results are shown in Fig. 4. The obtained average for four different observation windows is compared with each other to see the convergence pattern and decide on the appropriate observation window.

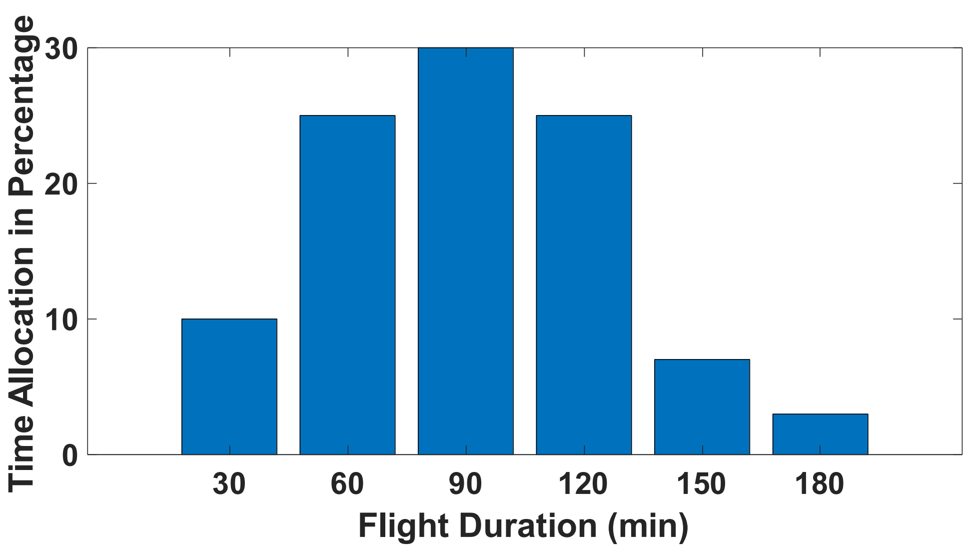


Fig. 2 Assumed pattern for requested flight durations versus the percentage of the requests.

As presented in Fig. 4, the daily average values for the 2-hour observation window for different days are far different from each other and smaller compared to other windows which indicates a great divergence. While moving forward to smaller observation windows, it can be seen that the results of five days for each observation window are getting closer and higher in value which is much more reasonable. The number of UAM vehicles exhibits considerable convergence starting from the 30-minute observation window and is improved as the window becomes even smaller. It is obvious that for smaller observation windows the convergence will be better, but as the goal is to make a compromise between the simulation time and the accuracy of the results, the 30-minute observation window is the proper choice to be implemented in our future simulations.

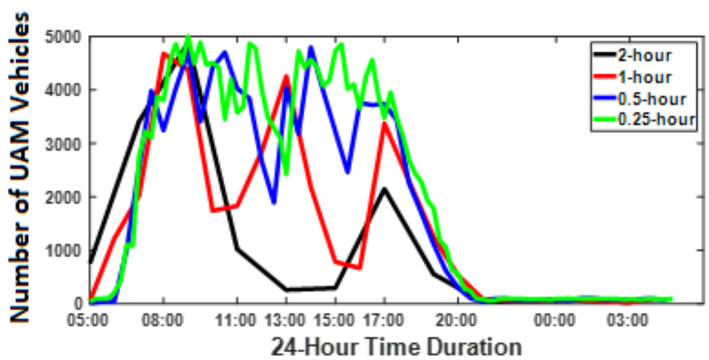


Fig. 3 Number of active UAM vehicles for four different observation windows throughout 24 hours.

After selecting the proper observation window, the case of real data reported from FAA for General Aviation aircraft has been simulated, similar to the case for urban air mobility. In other words, instead of making some assumptions, a data that gives some information about the number of commercial flights with their flight durations during 24-hour of a typical day (a busy day in NAS) and a data representing the expected demand profile during 24 hours of the day is being used.

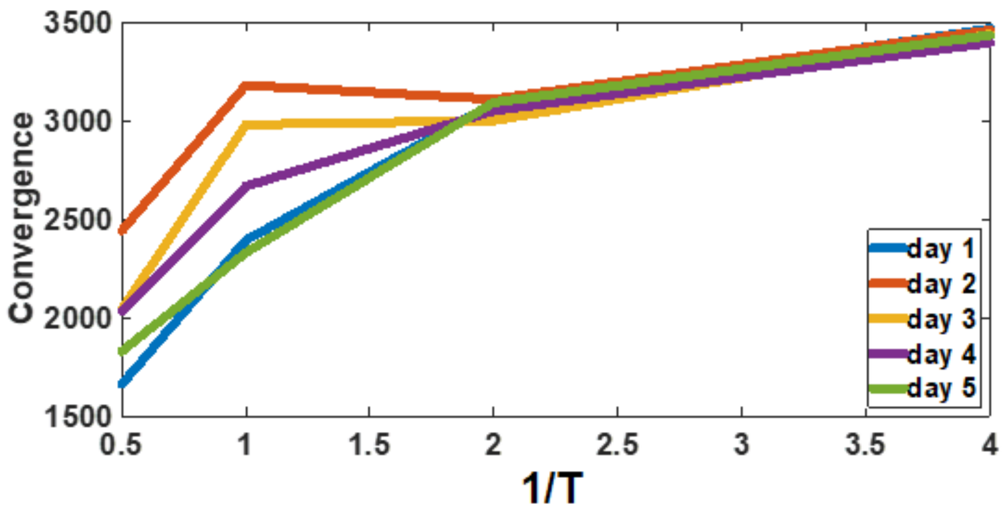


Fig. 4 Average number of active UAM vehicles for four different observation windows and five typical days.

Here, the simulations have been conducted based on real data. As there is no real data for UAM operations in hand yet, the two sets of assumptions used are based on the real data from FAA for General Aviation aircraft. Data presented in Fig. 5 gives some information about the pattern for the number of commercial flights during the 24 hours of the day, which has been used as the expected demand profile for the UAM vehicles.

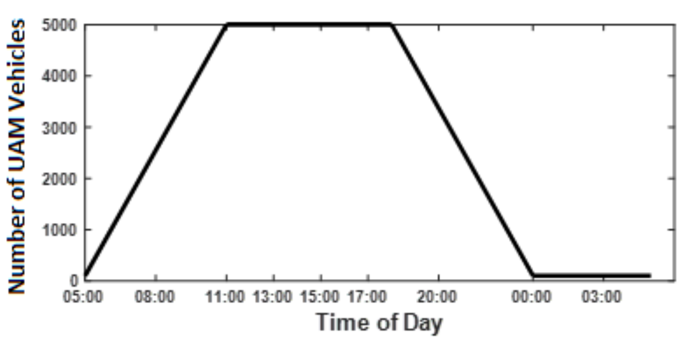


Fig. 5 Expected demand profile of the ICAO address requests throughout 24 hours.

Based on what is displayed in Fig. 5, the number of active UAM vehicles will increase from 5:00 am in the morning through 11:00 am. It will then stay at its maximum through 6:00 pm and then will decrease to its minimum and stays there until the next day. Data presented in Fig. 6, gives information about the durations of the flights in a typical day (a busy day in NAS), which was obtained from FAA. This data is used to show the percentage of UAM vehicles versus their requested flight durations. The minimum and maximum allowed flight durations are 1 and 5 hours, respectively. It is worth noting that the developed analysis tool is completely independent of the assumptions and whenever any real data is available for the UAM operations, these assumptions can be substituted with the new data.

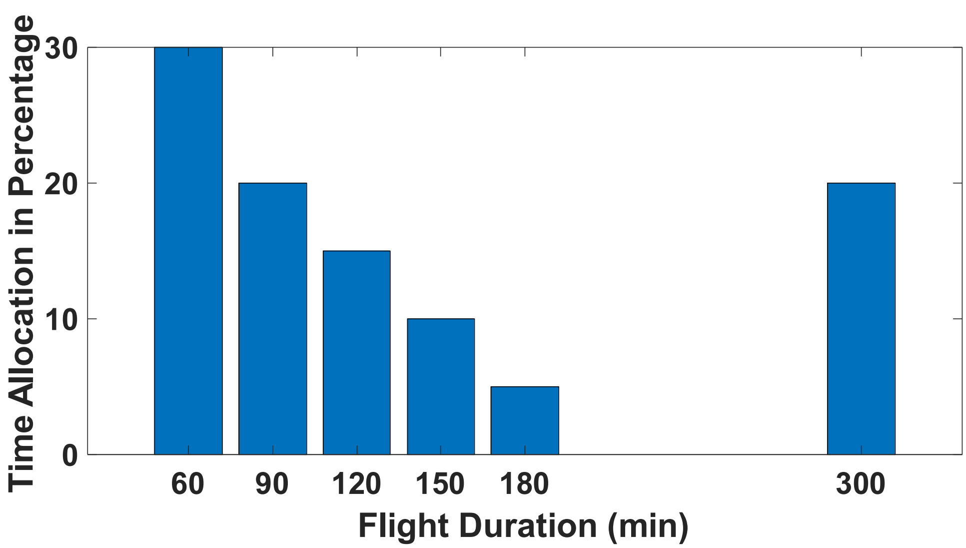


Fig. 6 Considered pattern for requested flight durations based on the percentage of the requests.

Based on the illustrated data, the simulations have been conducted for a typical day in a city with a known number of registered UAM vehicles considering a 30-minute observation window and the results have been analyzed based on these assumptions. A Monte Carlo-based simulation has been conducted to simulate the case and the results for a typical day are presented in Fig. 7.

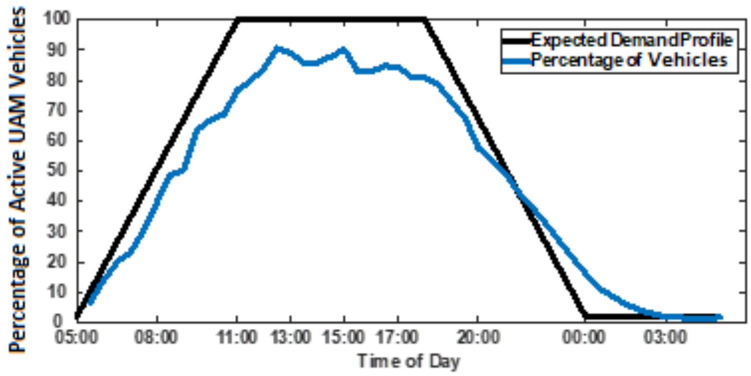


Fig. 7 Percentage of active UAM vehicles throughout 24 hours of the day.

As shown in Fig. 7, the number of active UAM vehicles is increasing from 5:00 am and reaches close to its maximum in the busy period of the day which is considered 11:00 am to 6:00 pm based on Fig. 5. Then, the number of UAM vehicles is decreasing till reaching its minimum after midnight. Before moving to the stage of deciding on the approximate number of ICAO addresses needed to be allocated to a city with this expected demand profile, a simulation should be conducted to select the number of typical days the simulation needs to be run to get the desired results. To do this, for different number of days, the number of active UAM vehicles has been averaged at each observation window and the results have been presented in Fig. 8.

As depicted in Fig. 8, a noticeable smoothness has happened comparing the cases of 10, 15, 20, 25 and 30 days with the 5-days case. Selecting 10 as the number of days seems to be the proper choice for running the simulations which guarantees the desired converging results.

2.5 New Definition for the Average

As discussed in the previous section, the approximate number of addresses needed for a city with a known number of UAM vehicles cannot be decided by averaging the number of active UAM vehicles throughout the whole day. Hence, a new definition for the average has been proposed to provide a rough estimation of the number of active UAM vehicles in the busy periods of the day. To do this, the number of active UAM vehicles has been averaged only at the busy period of the day. This is because if the number of allocated addresses is decided based on the busy period, there will be enough addresses for non-busy times as well. However, if the decision is made based on the average of a whole day, from what is shown in Fig. 10, due to the smaller value of the average in comparison to the number of UAM vehicles at the busy period, enough addresses could not be provided to the requests. If the average number of UAM vehicles in the busy period is considered, the results will be as shown in Fig. 11, which is around 80% of all registered UAM vehicles in the city and can roughly guarantee that it is a reliable definition to decide on the number of addresses needed.

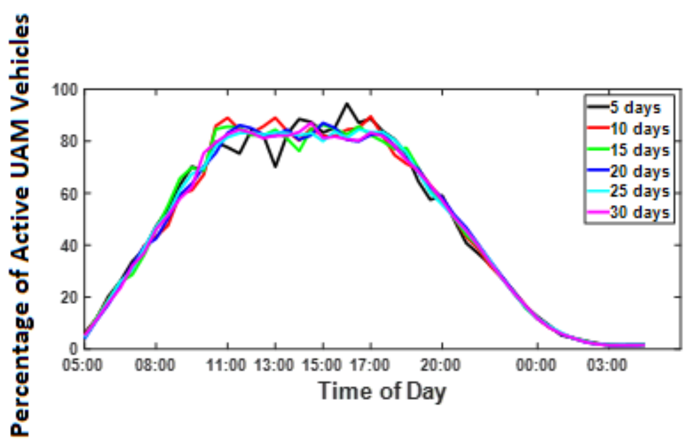


Fig. 8 Percentage of UAM vehicles for different number of days throughout 24 hours.

To select the proper number of addresses for a city with a known number of registered UAM vehicles, the average number of active UAM vehicles is needed, but is not enough. One suggestion to make the estimate more precise is to consider both the average and the standard deviation value. This will provide a better picture of the traffic flow throughout the day and can make the decision easier. Furthermore, there is a need to know the average number of active UAM vehicles in busy periods for the specific number of days to ensure the convergence of the results. By looking at the results, as presented in Fig. 11, on average, approximately 80% of the registered UAM vehicles are active during the busy periods and this is independent of the number of days the simulation is being run for. Based on the results from Fig. 11, a number roughly close to 80% of the total registered UAM vehicles will accommodate the average number of active UAM vehicles in the busy periods and if selected as the total available number of addresses, there will be a probability of denying some requests. In order to make sure that the number of addresses is appropriate, a tolerable percentage of denials should be defined. Comparing these results with what is displayed in Fig. 10, the results are approximately close, and these two graphs can help to make the final decision on the number of addresses needed. If the number of addresses is considered approximately 80% - 85% of the UAM vehicles, it can be ensured that there will be enough addresses to allocate in our busy periods.

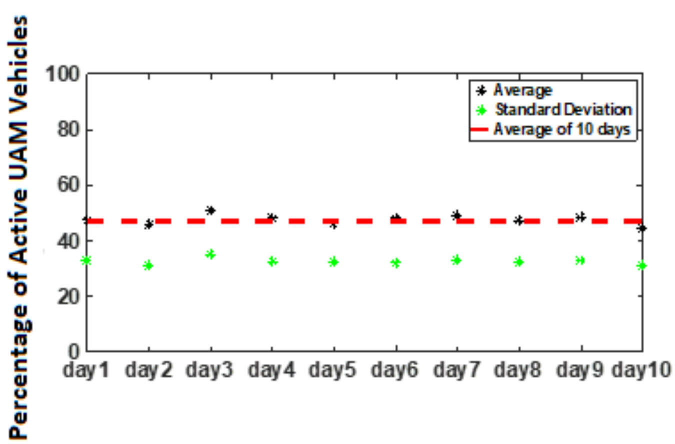


Fig. 9 Percentage of active UAM vehicles throughout 24 hours for 10 typical days.

According to the results obtained from the simulation, the proper observation window was chosen and by using that, the approximate number of addresses needed for a city with 5000 UAM vehicles could be decided. This number in some cases may not accommodate all the requests as it is less than the number of UAM vehicles in the city, but it roughly guarantees that it can cover the majority of the requests in busy periods of the day.

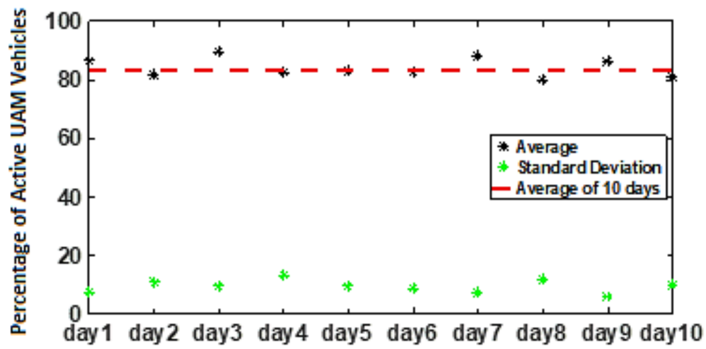


Fig. 10 Percentage of active UAM vehicles throughout the busy period for 10 typical days.

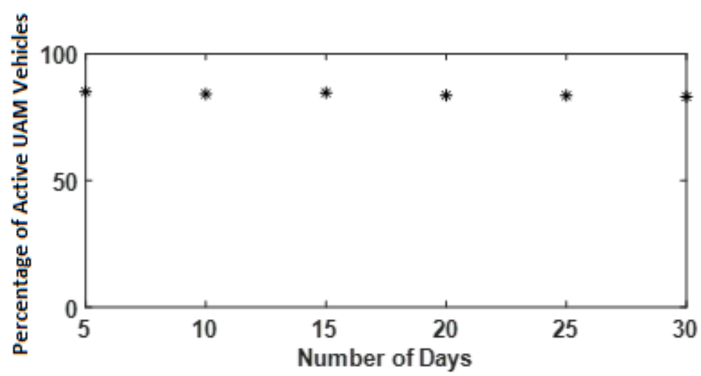


Fig. 11 Percentage of active UAM vehicles in the busy period for different number of days.

As discussed, due to the address scarcity problem for the UAM, the exact number of addresses cannot be allocated based on the number of UAM vehicles to the cities. The conducted simulations and discussions presented illustrate that it is possible to accommodate the address requests throughout the day, although there is a smaller number of addresses compared to the number of UAM vehicles in the city. According to this discussion, these results are obtained based on the Monte Carlo simulations, and they are showing a probability, not a certainty, to forecast the future. Based on these results, it can be concluded that it is very likely to be able to accommodate the requests in busy times with a smaller number of addresses. If otherwise, there should be a technique to take care of the denied requests and a plan to control the high address demands in busy periods of the day.

2.6 Conclusion

In this section, on order to analyze the traffic flow patterns of the UAM vehicles, two different sets of simulations were conducted. The first set led to the proper observation window for the simulations and the second set explored a solution to determine the approximate number of ICAO addresses needed to accommodate the desired number of UAM vehicles. This technique would be a solution for the address scarcity problem of the UAM vehicles. In the next section, the effect of applying different restrictions on the address assigning process, changing the allowed flight durations, or setting different prices for different flight durations, will be discussed.

2.7 References

[1] Holden, J., and Goel, N., "Fast-Forwarding to a Future of On-Demand, Urban Air Transportation," Uber Elevate, Uber White Paper, San Francisco, CA, Oct. 2016.

[2] Moore, M., Goodrich, K., Viken, J., Smith, J., Fredericks, B., Trani, T., Barraclough, J., German, B., and Patterson, M., "High Speed Mobility through On-Demand Aviation," Aviation Technology, Integration, and Operations Conference, AIAA Paper 2013-4373, 2013.
https://doi.org/10.2514/6.2013-4373

[3] Mueller, E., Kopardekar, P., and Goodrich, K., "Enabling Airspace Integration for High-Density On-Demand Mobility Operations," 17th AIAA Aviation Technology, Integration, and Operations Conference, AIAA Aviation Forum, AIAA Paper 2017-3086, 2017.
https://doi.org/10.2514/6.2017-3086

[4] Moore, M., "Concept of Operations for Highly Autonomous Electric Zip Aviation," 12th Aviation Technology, Integration and Operations (ATIO) Conference, AIAA Paper 2012-5472, 2012.
https://doi.org/10.2514/6.2012-5472

[5] Patterson, M., German, B., and Moore, M., "Performance Analysis and Design of On Demand Electric Aircraft Concepts," 12th Aviation Technology, Integration and Operations (ATIO) Conference, AIAA Paper 2012-5474, 2012.
https://doi.org/10.2514/6.2012-5474

[6] Smith, J., Viken, J., Guerreiro, N., Dollyhigh, S., Fenbert, J., Hartman, C., Kwa, T., and Moore, M., "Projected Demand and Potential Impacts to the National Airspace System of Autonomous, Electric, On-Demand Small Aircraft," 12th Aviation Technology, Integration and Operations (ATIO) Conference, AIAA Paper 2012-5595, 2012.
https://doi.org/10.2514/6.2012-5595

[7] Vascik, P. D., and Hansman, R. J., "Systems-Level Analysis of on Demand Mobility for Aviation," International Center for Air Transportation (ICAT) Rept. ICAT-2017-02, Massachusetts Institute of Technology, Cambridge, MA, Feb. 2017.

[8] Kopardekar, P., Rios, J., Prevot, T., Johnson, M., Jung, J., and Robinson, J., "Unmanned Aircraft System Traffic Management (UTM) Concept of Operations," Aviation Technology, Integration and Operations Conference, AIAA Paper 2016-3292, 2016.
https://doi.org/10.2514/6.2016-3292

[9] Rorie, R. C., Fern, L., and Shively, R. J., "The Impact of Suggestive Maneuver Guidance on UAS Pilots Performing the Detect and Avoid Function," Infotech@Aerospace, AIAA Paper 2016-1002, 2016.
https://doi.org/10.2514/6.2016-1002

[10] Rorie, R. C., Fern, L., Roberts, Z., Monk, K., Santiago, C., and Shively, R. J., "Validation of Minimum Display Requirements for a UAS Detect and Avoid System," Aviation Technology, Integration, and Operations Conference, AIAA Paper 2017-4483, 2017.
https://doi.org/10.2514/6.2017-4483

[11] Jang, D. S., Ippolito, C., Sankararaman, S., and Stepanyan, V., "Concepts of Airspace Structures and System Analysis for UAS Traffic Flows for Urban Areas," Infotech@Aerospace, AIAA Paper 2017-0449, 2017.
https://doi.org/10.2514/6.2017-0449

[12] Salleh, M., Tan, D. Y., Koh, C. H., and Low, K. H., "Preliminary Concept of Operations (ConOps) for Traffic Management of Unmanned Aircraft Systems (TM-UAS) in Urban Environment," Infotech@Aerospace, AIAA Paper 2017-0223, 2017.
https://doi.org/10.2514/6.2017-0223

[13] Holmes, B., Parker, R., Stanley, D., McHugh, P., Garrow, L., Masson, P., and Olcott, J., "NASA Strategic Framework for On-Demand Air Mobility," NASA NNL13AA08B, Hampton, VA, Jan. 2017.

[14] Duan, P., and Rankin, J., "ADS-B Feasibility Study for Commercial Space Flight Operations," 29th Digital Avionics Systems Conference, IEEE Publ., Piscataway, NJ, 2010, pp. 3.A.1-1–3.A.1-11.
https://doi.org/10.1109/DASC.2010.5655472

[15] Duan, P., and Rankin, J., "ADS-B Space-Oriented Message Set Design," 2011 Integrated Communications, Navigation, and Surveillance Conference Proceedings, IEEE Publ., Piscataway, NJ, 2011, pp. O2-1–O2-12.
https://doi.org/10.1109/ICNSURV.2011.5935353

[16] Leiden, K., Kopardekar, P., and Green, S., "Controller Workload Analysis Methodology to Predict Increases in Airspace Capacity," Aviation Technology, Integration, and Operations Conference, AIAA Paper 2003-6808, 2003.
https://doi.org/10.2514/6.2003-6808

[17] International Civil Aviation Organization, "Registration of Aircraft Addresses with Mode S Transponders," Third Meeting of North American, Central American and Caribbean Directors of Civil Aviation (NACC/DCA/3 - WP/05), Montreal, Canada, Sept. 2008.

[18] Lascara, B., Spencer, T., DeGarmo, M., Lacher, A., Maroney, D., and Guterres, M., "Urban Air Mobility Landscape Report: Initial Examination of a New Air Transportation System," Rept. 18-0154-4, MITRE Corp., Bedford, MA, April 2018.

[19] Erzberger, H., "Transforming the NAS: The Next Generation Air Traffic Control System," NASA TP-2004-212828, Oct. 2004.

[20] Gawdiak, Y., Holmes, B., Sawhill, B., Herriot, J., Ballard, D., Eckhause, J., Long, D., Hemm, R., Creedon, J., Murphy, C., Thompson, T., Wieland, F., Price, G., Marcolini, M., Moore, M., and Alcabin, M., "Air Transportation Strategic Trade Space Modeling and Assessment Through Analysis of On-Demand Air Mobility with Electric Aircraft," Aviation Technology, Integration, and Operations Conference, AIAA Paper 2012-5594, 2012.
https://doi.org/10.2514/6.2012-5594

[21] Ghayouraneh, S., El-Ghazaly, S., and Rankin, J., "Dynamic Addressing for On-Demand Mobility," 2018 Aviation Technology, Integration, and Operations Conference, AIAA Aviation Forum, AIAA Paper 2018-4152, 2018.
https://doi.org/10.2514/6.2018-4152

[22] Ghayouraneh, S., Rankin, J. M., and El-Ghazaly, S. M., "Practical Considerations in Traffic Flow Systems for ODM Vehicles," 2019 Integrated Communications, Navigation and Surveillance Conference (ICNS), IEEE Publ., Piscataway, NJ, 2019, pp. 1–7.
https://doi.org/10.1109/ICNSURV.2019.8735402

[23] Ghayouraneh, S., El-Ghazaly, S. M., and Rankin, J. M., "Investigation of Traffic Flow for ODM Vehicles in Dynamic ICAO Addressing Process," AIAA Aviation Forum, AIAA Paper 2019-3627, 2019.
https://doi.org/10.2514/6.2019-3627

Chapter 3

Monte Carlo Simulations to Predict Traffic Flow Patterns of UAM Vehicles

Authors: Sara Ghayouraneh, James M. Rankin, Samir M. El-Ghazaly

3.1 Introduction

With the fast pace of population growth, traffic and gridlocks are increasing each day. People are wasting a notable amount of their time in traffic while traveling to work and back home, especially in larger cities. This valuable time can be used to grow economies at work or spent with family [1]. Due to the major problems caused by traffic, mainly in congested cities, researchers are looking for a solution to solve this serious problem. On-demand mobility (ODM) or urban air mobility (UAM) concepts have been introduced which are believed to alleviate the traffic congestion by moving a part of urban transportation from the ground to the air [2-3].

The importance of future urban air transportation and the challenges it presents have been widely discussed [1]. These challenges are explained from both design and ATM points of view, and we provide some possible solutions. This article outlines a broad view of future UAM services and describes different approaches for UAM-related traffic management [4-7]. The authors utilized a Monte Carlo simulation technique to model the probability of different outcomes in a process that cannot be easily predicted due to random variables.

In order to be prepared for launching UAM, the structure of the airspace should be ready to accept operations of the new air vehicles [8]. Although some of the challenges regarding the management of airspace for UAM vehicles are similar to other air vehicles such as UAS, some other challenges become more difficult with the presence of the UAM vehicles [9-12]. The altitude of operation for UAS is at 400 ft. or less where no other air vehicle operates and technologies like detect and avoid (DAA) systems can be used to avoid collision [10-12], but as the UAM vehicles are categorized as manned vehicles and the operating altitude for them is considered to be at 1000 – 3000 ft. above ground level, traffic management becomes more challenging [13]. In order to manage the air traffic while different air vehicles are operating at different altitudes, various technologies can be used, especially the Automatic Dependent Surveillance-Broadcast (ADS-B) system [14-15]. However, for this system to be used in UAM vehicles, some modifications need to be made, especially to the message structure [15].

3.2 ADS-B System Usage for UAM Vehicles

The ADS-B system enables building a reliable communication between the aircraft and ATM on the ground or other aircraft. Communications can be utilized on either the 1090 MHz or 978 MHz frequencies. The 1090 MHz frequency is already so congested that is unable to accept more clients, but the 978 MHz can still be a potential frequency for UAM-related communications. As a long-term solution, a frequency specifically assigned to the UAM communications might be needed before the 978 MHz runs out of its capacity. However, adding a third frequency would add complexity to any interoperability. One of those complexities is modifying the ADS-B message structure to be fitted into the UAM concept [16].

An ADS-B message has 112 bits and 24 of those are allocated to the International Civil Aviation Organization (ICAO) addressing field [17]. For an aircraft registered in the United States, the first 4 of the 24 bits are fixed to 1010 to represent the aircraft is flying in US airspace and the remaining bits create 2^20 combinations of unique addresses. Comparing the number of available unique addresses with the number of active general aviation (GA) aircraft in the US, only 20% of the available combinations are being used while the remaining 80% are being reserved for future use [18]. On the other hand, if the number of available addresses for the GA aircraft is compared to the number of registered active cars and trucks in the US, which is about 264 million, and assuming that only 1% of these will be UAM vehicles, this number will exceed the number of available addresses [19].

The first solution is to change the structure of the ADS-B message to provide a larger number of addresses. However, it is not feasible to design a capacity-specific protocol that must be revisited or redesigned every time substantial growth occurs [20-25]. The second solution is to use the remaining 80% of the addresses available for the GA aircraft to address the UAM vehicles. However, this can only be considered a short-term solution because there are not enough addresses. The third solution is to use one of the three sets of 4 bits (1011, 1101, and 1111) reserved for future use, specifically as the first 4 bits of the UAM vehicles' ICAO address, and this will open 2^20 available combination of addresses for them. Although this solution provides a larger number of addresses compared to the previous one, it is still not sufficient. The last solution is to use the dynamic ICAO addressing process. This process is very similar to the Dynamic Host Configuration Protocol (DHCP) system where an Internet Protocol (IP) address is assigned to a device when connecting to the internet; whenever it disconnects from the network, the address is released and can be assigned to another device upon connecting. In this technique, the addresses will be assigned to the UAM vehicles dynamically, and the UAM vehicle will temporarily lease their addresses instead of owning them [22- 25].

3.3 Dynamic ICAO Addressing Process for UAM Vehicles

In this approach, each UAM vehicle with a unique vehicle identification number (VIN) will request an address and a preferred flight duration prior to takeoff. VIN is selected to simplify the case, but any other unique numbering system can also be used. This request will be sent to an

ATM-like system on the ground which has access to the pool of available ICAO addresses (2^20 number of addresses considering the first 4 fixed bits). An address will randomly be chosen from the pool and sent back to the UAM vehicle. After the flight ends, the address will be released back to the pool of addresses to be reassigned to another UAM vehicle upon request [22-25]. Dynamic addressing provides a greater number of unique addresses and as it is automatic, it minimizes the errors that may occur if done manually.

In order to simulate the case, a statistical approach based on a Monte Carlo technique is used. The uncertainty behavior in predicting models is understood by the Monte Carlo technique and the likelihood of the outcome results are given. To study the traffic flow at the dynamic ICAO addressing process, an analysis tool was developed. A city with a known number of registered UAM vehicles is assumed for the simulations, but the developed analysis tool is independent of this number and can be scaled. Moreover, the simulation start time is assumed to be 5 a.m. and the traffic flow is studied throughout the day. In a previous study, we simulated traffic flow patterns at different observation windows throughout the day [22-25]. The simulation is conducted for four different observation windows (2 hours, 1 hour, 30 minutes, and 15 minutes) and the results for the 30-minute observation window provide the balance between accuracy and complexity. Thus, the 30-minute window was selected for all simulations presented in this study. Simulations are conducted to illustrate the necessary amount of ICAO addresses to accommodate the maximum number of UAM vehicles for multiple case studies. Based on the results from a previous study, to decide on the number of ICAO addresses allocated to an area with a determined number of registered UAM vehicles, the average number of active vehicles throughout busy periods of the day was calculated.

3.4 Analysis Scenarios

In order to simulate the case, two sets of assumptions have been considered. These assumptions are based on real data [26]. Due to the unavailability of real data for the UAM operations, two data sets were used from the FAA for GA aircraft. However, any other set of assumptions or real-case data would also be acceptable. The first data set displays the busy and non-busy periods of the day in US airspace, which is illustrated in Fig. 1. As it is shown, the number of active UAM vehicles is increasing starting from 5 through 11 a.m.; it stays at its maximum through 6 p.m. and then the number decreases back to its minimum through midnight. The pattern for the number of commercial flights is demonstrated by this data for 24 hours. The expected demand profile for the UAM vehicles is based on this pattern.

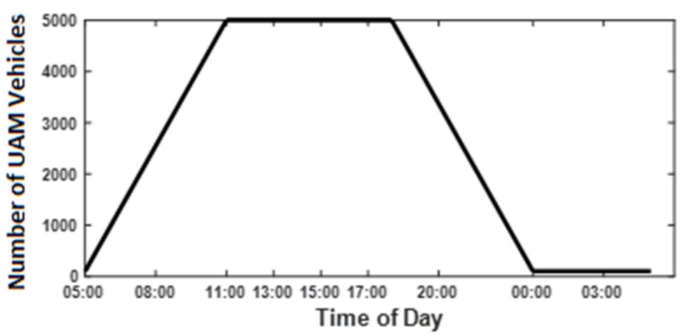


Fig. 1 Expected demand profile of the ICAO address requests throughout 24 hours.

The information regarding the flight durations in a typical day is provided in Fig. 2, which was also obtained from the FAA [26]. The percentage of UAM vehicles versus their requested flight duration is demonstrated in this figure. For the conducted simulations, the available flight durations were 1 hour, 1.5 hours, 2 hours, 2.5 hours, 3 hours, and 5 hours.

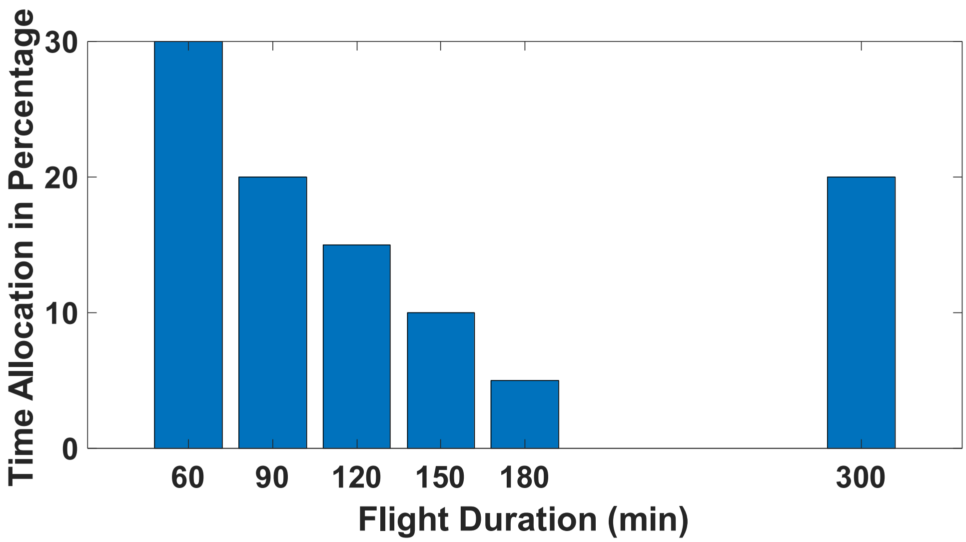


Fig. 2 Considered pattern for requested flight durations based on the percentage of the requests.

In the first step, the simulation is conducted based on assumptions for a typical day. Available flight durations are identified based on what is illustrated in Fig. 2. As mentioned before, the developed analysis tool is completely independent of the assumptions and whenever any real data is available for the UAM operations, these assumptions can be substituted with the new data. In order to study the traffic flow for this case, the Monte Carlo-based simulation results are presented in Fig. 3.

The blue line shown in Fig. 3 represents the traffic flow or the distribution of the number of active UAM vehicles throughout the day while considering that the maximum allowed flight duration is 5 hours. As represented in Fig. 3, in the busy period of the day (11a.m. to 6 p.m.) the number of active UAM vehicles is close to the maximum of the demand profile (5,000). Furthermore, in Fig. 4, a simulation has been conducted to study the average number of active vehicles throughout the busy period. This number could approximate the number of ICAO addresses that can accommodate the maximum number of UAM vehicles in an area.

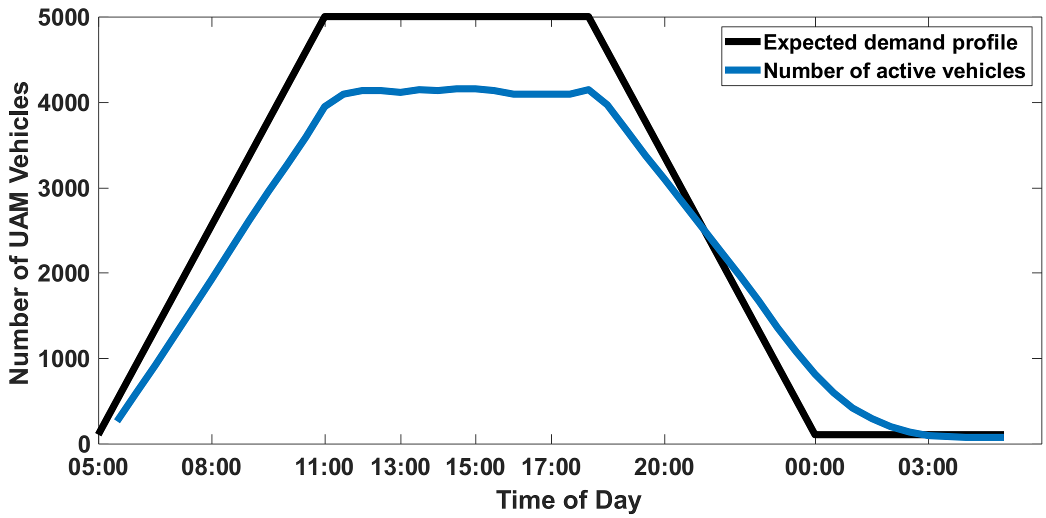


Fig. 3 Number of active UAM vehicles throughout the 24 hours of the day.

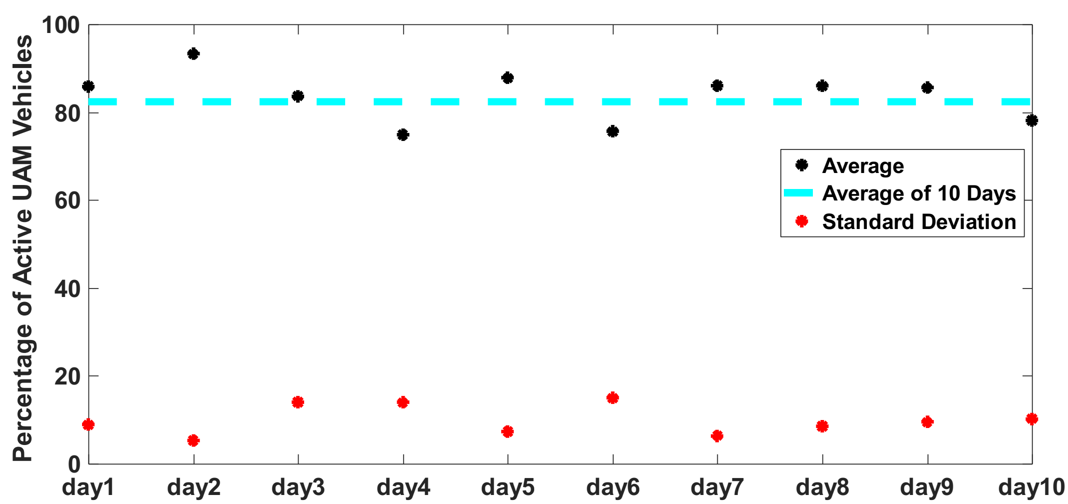


Fig. 4 Percentage of active UAM vehicles for 10 typical days.

As shown in Fig. 4, the average number of active UAM vehicles in the busy period is about 82%. However, to select the approximate number of ICAO addresses for this case, one should consider both the average and the standard deviation. Due to the address limitation, instead of allocating the same number of ICAO addresses as the number of registered UAM vehicles to a specific city or area, one should identify the most efficient number of ICAO addresses that can accommodate the maximum possible number of vehicles.

In order to alleviate the traffic in the high demand periods, multiple scenarios of possible policies and flexibilities will be introduced to observe the effect of each case on the traffic flow pattern. These scenarios are the variation of the maximum allowed flight duration, application of request denial strategies during peak usage, and a fee structure application during peak usage. This will predict the approximate number of ICAO addresses to allocate for each case.

3.4.1 Variation of the Maximum Allowed Flight Duration

The first scenario observed is the effect of decreasing the maximum allowed flight duration on the distribution of the number of UAM vehicles in the high demand periods. In this case, the maximum allowed flight duration is decreased from 5 hours to 3 hours to observe the effect of this reduction on the traffic flow. The flight durations that are available are 1 hour, 1.5 hours, 2 hours, 2.5 hours, and 3 hours. As shown in Fig. 5, the distribution of the number of active UAM vehicles has decreased when reducing the maximum allowed flight duration from 5 hours to 3 hours in the busy period. To calculate the approximate number of ICAO addresses needed to be allocated for this case, we studied the average number of active UAM vehicles and their standard deviation. As illustrated in Fig. 6, the average number has decreased compared to the previous case, which shows that decreasing the maximum allowed flight duration will reduce the number of active UAM vehicles in the high demand periods and accordingly, the number of ICAO addresses needed.

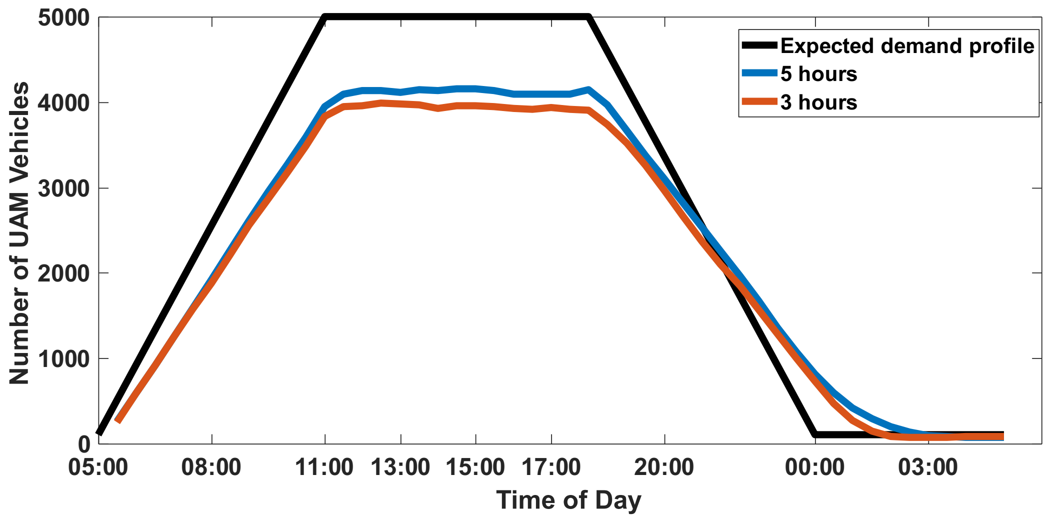


Fig. 5 Number of active UAM vehicles throughout 24 hours of the day.

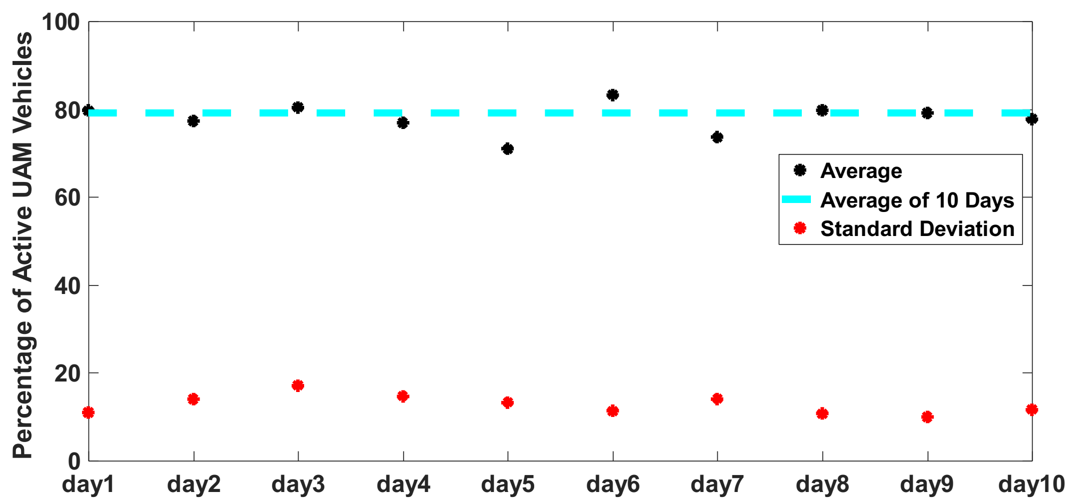


Fig. 6 Percentage of active UAM vehicles for 10 typical days.

Reduction in the number of active UAM vehicles in high demand periods by decreasing the maximum allowed flight duration from 5 hours to 3 hours prompted a similar simulation by lowering the maximum allowed flight duration to 2 hours and studying the effect of this reduction. In this case, the available flight durations are 1 hour, 1.5 hours, and 2 hours. As depicted in Fig. 7, the yellow line, which shows the traffic flow of the case with the maximum allowed flight duration of 2 hours, stays less than the two previous cases in the busy period. This proves that decreasing the maximum allowed flight duration will alleviate the traffic in higher demand periods. Fig. 8 illustrates the average number of active UAM vehicles for 10 typical days and as it is shown, the average number of active UAM vehicles has decreased from about 82% for the case with the maximum allowed flight duration of 5 hours to roughly 76%. Reducing the maximum allowed flight duration in higher demand periods can enable the traffic management section to accommodate a greater number of ICAO address requests.

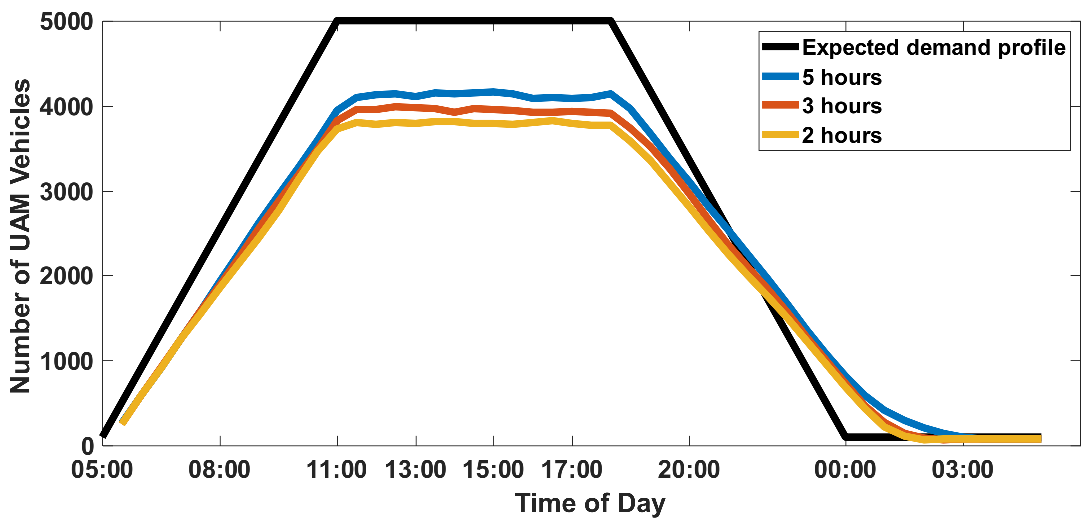


Fig. 7 Number of active UAM vehicles throughout 24 hours of the day.

In addition to studying the effect of decreasing the maximum flight duration for two different cases, a special case studies a situation where the only available flight duration is 1 hour. This case is studied mostly for the companies that are interested in last-mile deliveries, but they are dealing with the battery-limitation issues. In this case, the expiration duration for all of the ICAO addresses is 1 hour, and after this duration ends, the address will expire and be ready to be reassigned. As illustrated in Fig. 9, limiting the available flight duration to 1 hour noticeably decreased the number of active UAM vehicles in the high demand period. Studying the average number of active UAM vehicles in Fig. 10 shows a considerable decrease from about 82% for the case of maximum allowed flight duration of 5 hours to less than 70% for this case. Furthermore, a larger number of address requests can be accommodated due to the reduction in the number of active UAM vehicles in the busy period.

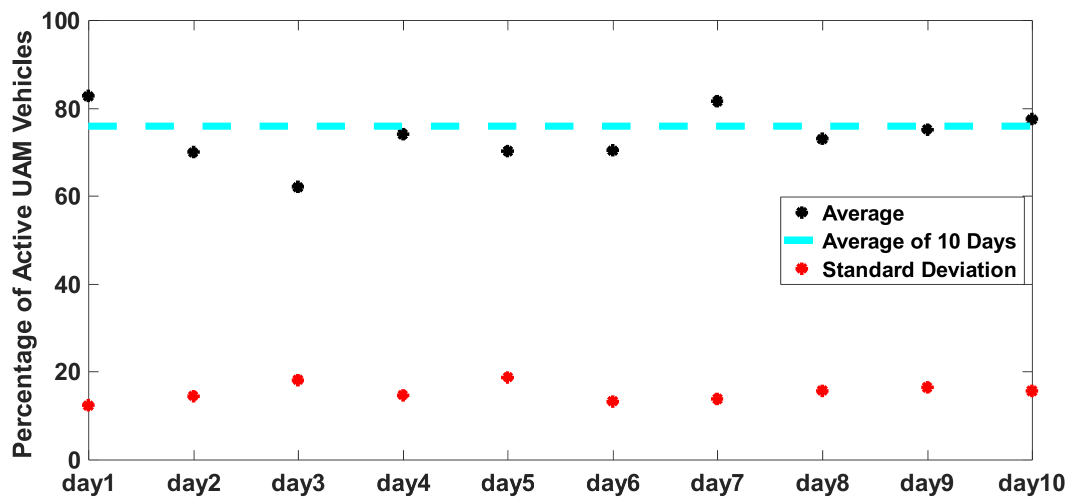


Fig. 8 Percentage of active UAM vehicles for 10 typical days.

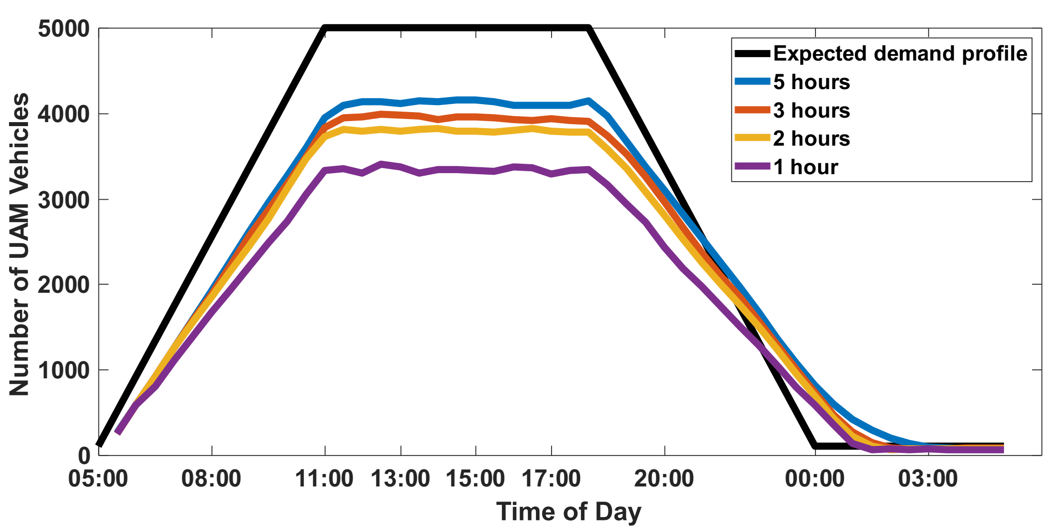


Fig. 9 Number of active UAM vehicles throughout 24 hours of the day.

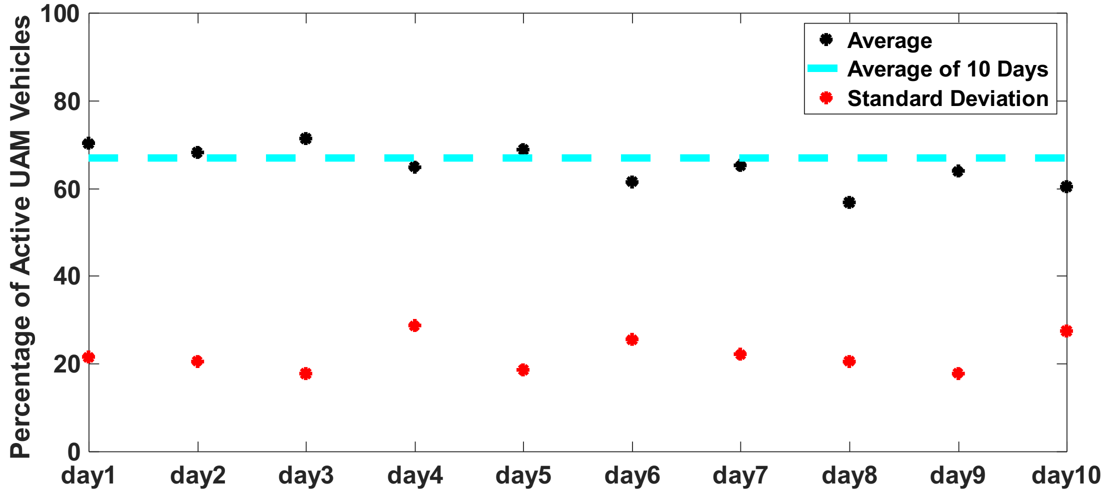


Fig. 10 Percentage of active UAM vehicles for 10 typical days.

3.4.2 Application of Static Request Denial

The second scenario shows a situation where a certain percentage of request denials can be tolerated. Defining the percentage of denials depends on the situation of the busy period. The reason for using the static term is that, in this case, a tolerable number of requests made throughout the high demand period will be denied, requiring the clients to go through the requesting process again. In this case, the percentage that can be tolerated to be denied is assumed to be 20%, but the developed analysis tool is completely independent of this number and can be scaled when needed. The simulation results associated with this case has been illustrated in Fig. 11 to observe the effect of denying a certain percentage of the requests on the traffic flow. As it is shown, the number of active UAM vehicles in the busy period stays less than the case without any denials. The average number of active UAM vehicles for the case of denying 20% of the requests made throughout the high demand period is illustrated in Fig. 12. As it is shown, this average has decreased from about 82% for a case without any denials to about 75%, which represents that denying a certain percentage of requests in the busy period will decrease the average number of active UAM vehicles, alleviate the traffic, and consequently, reduce the number of ICAO addresses needed to be allocated.

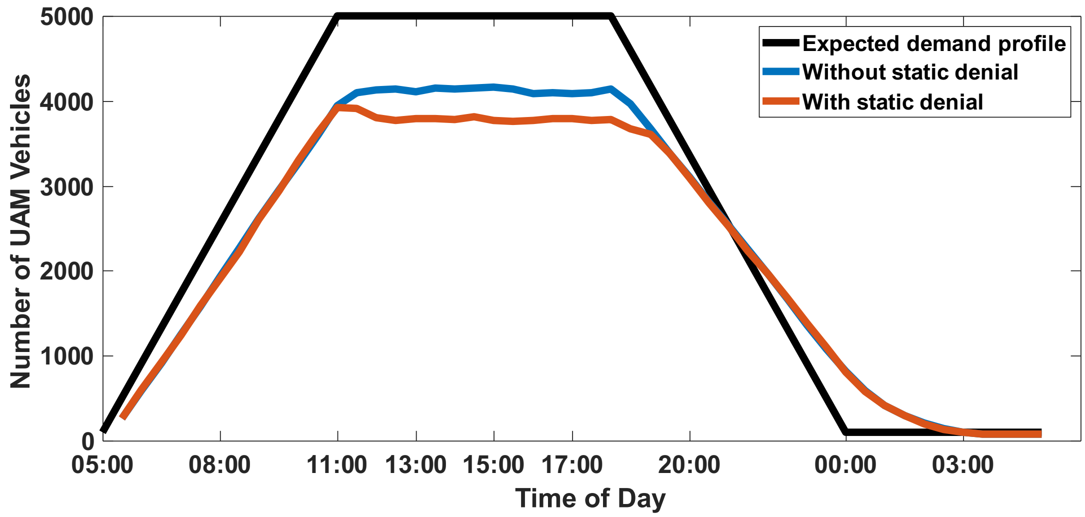


Fig. 11 Number of active UAM vehicles throughout 24 hours of the day (maximum allowed flight duration is 5 hours).

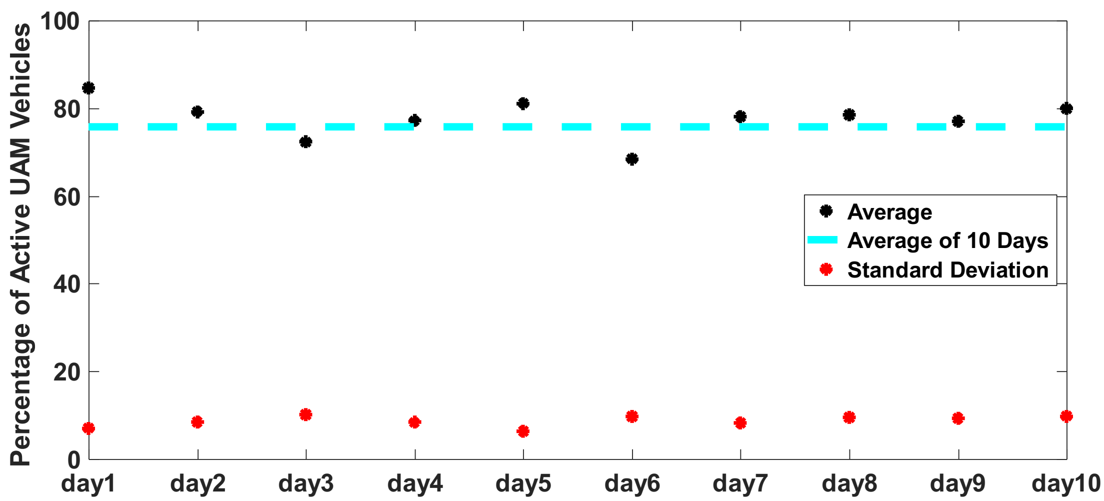


Fig. 12 Percentage of active UAM vehicles for 10 typical days (with static denial).

3.4.3 Application of Dynamic Request Denial

The third scenario is similar to the previous case where a certain percentage of the requests made in the high demand period will be denied due to the address limitation, but there will be no significant inconveniences to the clients. However, unlike the previous case where the requests were completely denied and the costumers with denied requests were responsible for re-requesting an address later, the clients will be waitlisted and assigned an address on a first-come, first-served basis. In this case, the customers whose requests were denied will enter a queue until an address is available. Fig. 13 represents the traffic flow pattern while dynamically denying 20% of the requests in the busy period. Comparing Fig. 11 and Fig. 13, which illustrate the traffic flow for the static and dynamic denials, respectively, illustrates that although the number of active UAM vehicles for the dynamic denial case stays slightly less than the case without any denials, it is still more than the number of active UAM vehicles for the static denial case.

The reason for this difference is that in the dynamic denial case, requests are not completely denied but instead waitlisted. Fig. 14 shows the average number of requests in the busy period of the day for the dynamic denial case. Comparing this with the average number of active UAM vehicles for the case without any denials, it shows a slight decline from about 82% to about 79%. However, this decrease is not as significant as the case with the static denial, which alleviates traffic faster than the dynamic case with the same denial percentages. However, in the case of dynamic denial, clients have the option to be waitlisted instead of their requests being outright denied.

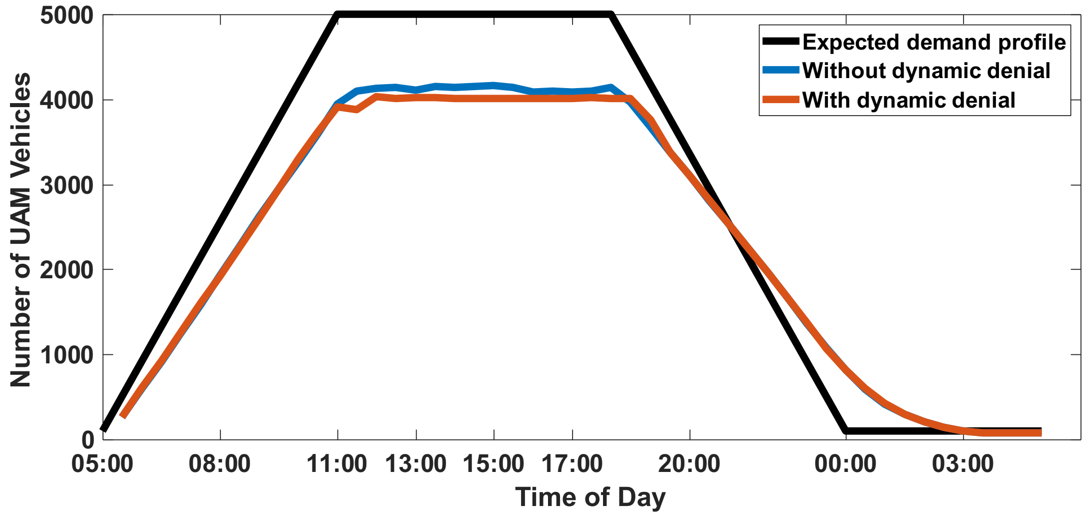


Fig. 13 Number of active UAM vehicles throughout 24 hours of the day (maximum allowed flight duration is 5 hours).

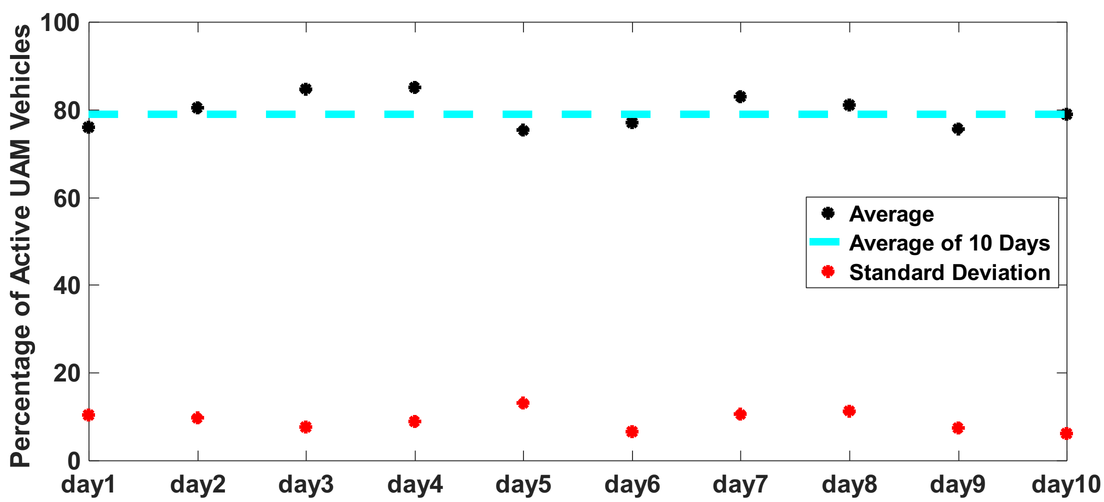


Fig. 14 Percentage of active UAM vehicles for 10 typical days (with dynamic denial).

3.4.4 Application of Price Adjustment

The fourth scenario studies the effect of applying price adjustment to the available flight durations – the longer the flight, the higher the hourly prices. The price assignment starts from the beginning of the high demand period and stops at the end of it. As illustrated in Fig. 15, the red line which represents traffic flow for the case with price adjustment stays considerably lower than the blue line associated with the case with no price adjustments in the busy period. At the point that the price adjustment has started, the number of active UAM vehicles starts to decrease, and when the price adjustment stops, the number of active UAM vehicles starts to increase which creates two peaks at the two ends of the red line. Fig. 16 shows the average number of active UAM vehicles for the case with price adjustment which has considerably reduced from 82% for the case with no price adjustments to about 62% for this case. This shows that applying price adjustments to flight durations and favoring shorter usage times alleviate traffic in the busy period and decreases the number of ICAO addresses needed for this case. However, for the system designer to select the approximate number of ICAO addresses, the two peaks at both ends of the busy period should be considered along with the average and the standard deviation as it will increase the number of addresses needed.

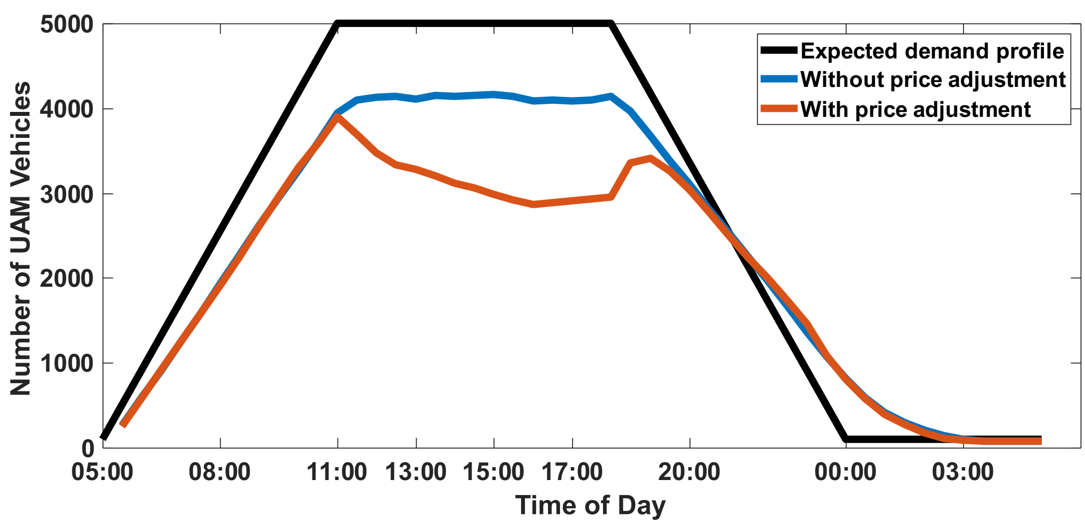


Fig. 15 Number of active UAM vehicles throughout 24 hours of the day (maximum allowed flight duration is 5 hours).

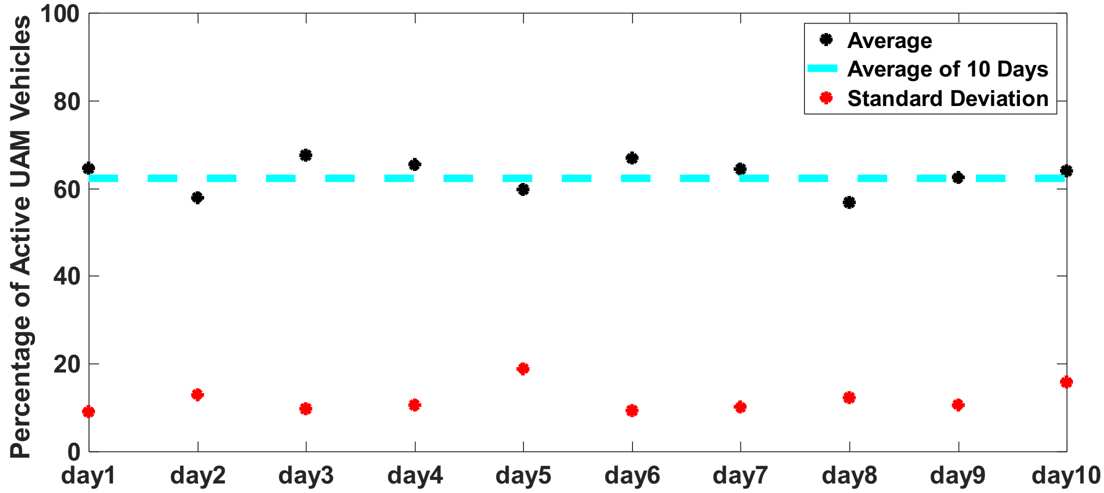


Fig. 16 Percentage of active UAM vehicles for 10 typical days (with price adjustment).

3.4.5 Application of Modified Price Adjustment

The final scenario observed is similar to the price adjustment case with some modifications. In this case, unlike the previous scenario, the price adjustment process will start 2 hours before the start time of the busy period and it will stop 2 hours after that period. The simulation results associated with this case are shown in Fig. 17 and Fig. 18. In Fig. 17, the yellow line which is associated with the case with modified price adjustment is smoother than the red line and does not have those two peaks at the two ends which reduces the number of ICAO addresses needed compared to the previous case. In other words, there is no need to consider the higher number of active UAM vehicles at the peaks which are the start and the endpoints of the busy period. Furthermore, there are benefits for using this modified price adjustment as it adjusts prices for the longer periods compared to the previous case. Thus, it generates additional revenue. Moreover, Fig. 18 illustrates the average number of active UAM vehicles for the modified price adjustment case which is slightly less than 60%, but the difference with this case is that there is no need to consider the average number of UAM vehicles at the peaks.

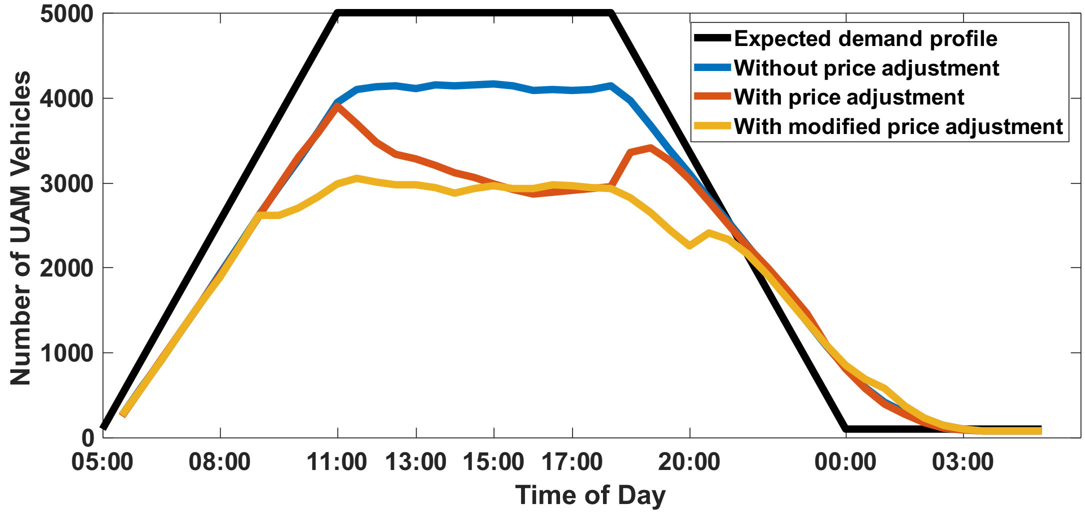


Fig. 17 Number of active UAM vehicles throughout 24 hours of the day (maximum allowed flight duration is 5 hours).

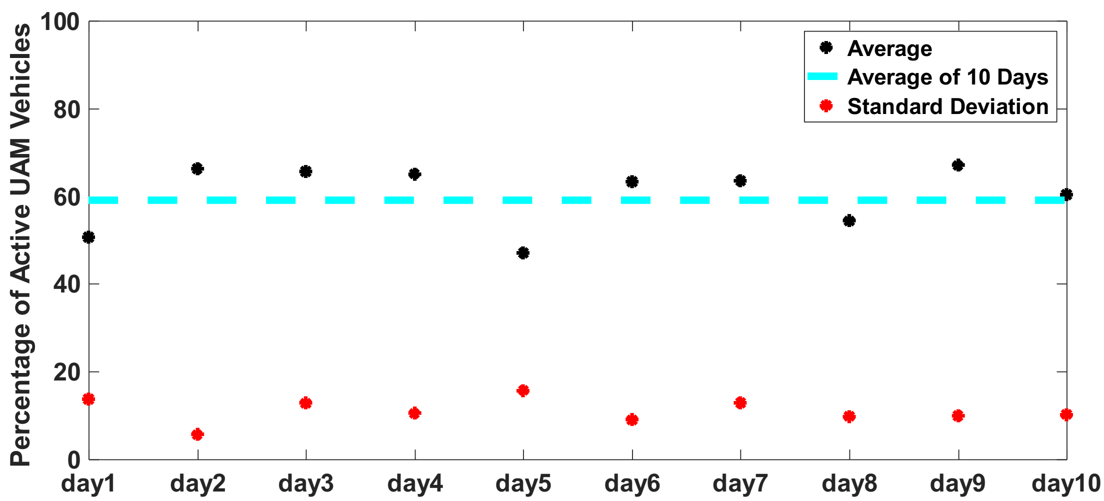


Fig. 18 Percentage of active UAM vehicles for 10 typical days (with modified price adjustment).

3.5 Conclusion

In this section, multiple scenarios of different policies and flexibilities and their impact on the distribution of the number of active UAM vehicles throughout the day were observed. Decreasing the maximum allowed flight duration in the busy periods of the day was approved to reduce the number of active UAM vehicles. The effect of static and dynamic denials was observed and was concluded that the static-denial approach alleviates the traffic faster, but the dynamic denial alternative is more fair, equitable, and adaptable as it offers the clients the option to be waitlisted. Overall, the dynamic-denial approach offers better customer service compared to the static one, and the price adjustment case is the most effective and flexible approach.

3.6 References

[1] Holden, J., and Goel, N., "Uber Elevate: Fast-Forwarding to a Future of On-Demand Urban Air Transportation," Uber Inc., San Francisco, CA, October 2016.

[2] Moore, M., Goodrich, K., Viken, J., Smith, J., Fredericks, B., Trani, T., Barraclough, J., German, B., and Patterson, M., "High Speed Mobility through On-Demand Aviation," In Aviation Technology, Integration, and Operations Conference, AIAA, Washington, D.C., 2013. https://doi.org/10.2514/6.2013-4373

[3] Mueller, E., Kopardekar, P., and Goodrich, K., "Enabling Airspace Integration for High-Density On-Demand Mobility Operations," 17th AIAA Aviation Technology, Integration, and Operations Conference, AIAA AVIATION Forum, 2017.
https://doi.org/10.2514/6.2017-3086

[4] Moore, M., "Concept of Operations for Highly Autonomous Electric Zip Aviation," 12th Aviation Technology, Integration and Operations (ATIO) Conference, Indianapolis, IN, 2012. https://doi.org/10.2514/6.2012-5472

[5] Patterson, M., German, B., and Moore, M., "Performance Analysis and Design of On-Demand Electric Aircraft Concepts," 12th Aviation Technology, Integration and Operations (ATIO) Conference, Indianapolis, IN, 2012.
https://doi.org/10.2514/6.2012-5474

[6] Smith, J., Viken, J., Guerreiro, N., Dollyhigh, S., Fenbert, J., Hartman, C., Kwa, T., and Moore, M., "Projected Demand and Potential Impacts to the National Airspace System of Autonomous, Electric, On- Demand Small Aircraft," 12th Aviation Technology, Integration and Operations (ATIO) Conference, Indianapolis, IN, 2012.
https://doi.org/10.2514/6.2012-5595

[7] Vascik, P. D., Hansman, R. J., "Systems-Level Analysis of On Demand Mobility for Aviation," International Center for Air Transportation (ICAT), MIT, ICAT-2017-02, February 2017.

[8] Kopardekar, P., Rios, J., Prevot, T., Johnson, M., Jung, J., and Robinson, J., "Unmanned Aircraft System Traffic Management (UTM) Concept of Operations," In Aviation Technology, Integration and Operations Conference, AIAA, Washington, D.C., 2016. https://doi.org/10.2514/6.2016-3292

[9] Rorie, R. C., Fern, L., and Shively, R. J., "The Impact of Suggestive Maneuver Guidance on UAS Pilots Performing the Detect and Avoid Function," In Infotech@ Aerospace, AIAA, Washington, D.C., 2016.
https://doi.org/10.2514/6.2016-1002

[10] Rorie, R. C., Fern, L., Roberts, Z., Monk, K., Santiago, C., and Shively, R. J., "Validation of Minimum Display Requirements for a UAS Detect and Avoid System," In Proceedings of the

Aviation Technology, Integration, and Operations Conference, AIAA, Washington D.C., 2017. https://doi.org/10.2514/6.2017-4483

[11] Jang, D. S., Ippolito, C., Sankararaman, S., and Stepanyan, V., “Concepts of Airspace Structures and System Analysis for UAS Traffic Flows for Urban Areas,” In Infotech@Aerospace, AIAA, Washington D.C., 2017.
https://doi.org/10.2514/6.2017-0449

[12] Salleh, M., Tan, D. Y., Koh, C. H., and Low, K. H., “Preliminary Concept of Operations (ConOps) for Traffic Management of Unmanned Aircraft Systems (TM-UAS) in Urban Environment,” In Infotech@Aerospace, AIAA, Washington, D.C., 2017. https://doi.org/10.2514/6.2017-0223

[13] Holmes, B., Parker, R., Stanley, D., McHugh, P., Garrow, L., Masson, P., and Olcott, J., “NASA Strategic Framework for On-Demand Air Mobility,” NASA Contract No: NNL13AA08B, Hampton, VA, January 2017.

[14] Duan, P., and Rankin, J., “ADS-B Feasibility Study for Commercial Space Flight Operations,” 29th Digital Avionics Systems Conference, Salt Lake City, UT, 2010. https://doi.org/10.1109/DASC.2010.5655472

[15] Duan, P., and Rankin, J., “ADS-B Space-Oriented Message Set Design,” 2011 Integrated Communications, Navigation, and Surveillance Conference Proceedings, Herndon, VA, 2011. https://doi.org/10.1109/ICNSURV.2011.5935353

[16] Leiden, K., Kopardekar, P., and Green, S., “Controller Workload Analysis Methodology to Predict Increases in Airspace Capacity,” In Aviation Technology, Integration, and Operations Conference, AIAA, Washington, D.C., 2003.
https://doi.org/10.2514/6.2003-6808

[17] International Civil Aviation Organization, “Registration of Aircraft Addresses with Mode S Transponders,” Third Meeting of North American, Central American and Caribbean Directors of Civil Aviation (NACC/DCA/3), Punta Cana, Dominican Republic, September 2008.

[18] https://www.aopa.org/about/general-aviation-statistics/active-general-aviation-aircraft-in-the-u-s

[19] Lascara, B., Spencer, T., DeGarmo, M., Lacher, A., Maroney, D., and Guterres, M., “Urban Air Mobility Landscape Report: Initial Examination of a New Air Transportation System,” The MITRE Corporation, April 2018.

[20] Erzberger, H., “Transforming the NAS: The Next Generation Air Traffic Control System,” NASA/TP-2004-212828, October 2004.

[21] Gawdiak, Y., Holmes, B., Sawhill, B., Herriot, J., Ballard, D., Eckhause, J., Long, D., Hemm, R., Creedon, J., Murphy, C., Thompson, T., Wieland, F., Price, G., Marcolini, M., Moore, M., and

Alcabin, M., “Air Transportation Strategic Trade Space Modeling and Assessment Through Analysis of On-Demand Air Mobility with Electric Aircraft,” In Aviation Technology, Integration, and Operations Conference, AIAA, Washington D.C., 2012. https://doi.org/10.2514/6.2012-5594

[22] Ghayouraneh, S., El-Ghazaly, S., and Rankin, J., “Dynamic Addressing for On-Demand Mobility,” 2018 Aviation Technology, Integration, and Operations Conference, AIAA AVIATION Forum, 2018.
https://doi.org/10.2514/6.2018-4152

[23] Ghayouraneh, S., Rankin, J. M., and El-Ghazaly, S. M., “Practical Considerations in Traffic Flow Systems for ODM Vehicles,” 2019 Integrated Communications, Navigation and Surveillance Conference (ICNS), Herndon, VA, USA, 2019, pp. 1-7. https://doi.org/10.1109/ICNSURV.2019.8735402

[24] Ghayouraneh, S., El-Ghazaly, S. M., and Rankin, J. M., “Investigation of Traffic Flow for ODM Vehicles in Dynamic ICAO Addressing Process,” AIAA AVIATION Forum, AIAA, 2019. https://doi.org/10.2514/6.2019-3627

[25] Ghayouraneh, S., Rankin, J. M., and El-Ghazaly, S. M., “Dynamic Addressing for Urban Air Mobility Vehicles,” Journal of Air Transportation, Vol. 0, No. 0, pp. 1-4, 2020. https://doi.org/10.2514/1.D0207

[26] https://www.faa.gov/air_traffic/by_the_numbers/media/Air_Traffic_by_the_Numbers_2019

Chapter 4

Monte-Carlo-Based Analysis of Inter-City and Intra-city Travels of UAM Vehicles

Authors: Sara Ghayouraneh, James M. Rankin, Samir M. El-Ghazaly

4.1 Introduction

Rapid population growth increases the demand for a fast and easy mode of transportation. Urban Air Mobility is a recently introduced concept where the UAM vehicles take charge of a portion of the urban transportation [1-3]. By switching a part of urban transportation to the air, the traffic on the ground is alleviated. Many challenges have already been identified regarding the concept of Urban Air Mobility [4-7]. One of these challenges is the traffic management and the presence of a control system that manages the traffic in the UAM-related part of the airspace [8-9]. As discussed in previous sections, the Automatic Dependent Surveillance-Broadcast (ADS-B) system with some modifications, especially in the message structure [10-11], along with introducing the dynamic ICAO addressing concept was considered as one of the technologies that can be used to facilitate the traffic management of the UAM [12-16].

In previous sections, a single area/city with a specified number of UAM vehicles have been assumed for the simulations and using the developed analysis tool, the traffic flow pattern and the number of addresses needed for different cases were predicted. It is worth noting that the tool is independent of the assumptions and the results can be reproduced based on any new data. In this section, the developed analysis tool using the Monte-Carlo simulation technique, considering the dynamic addressing, predicts the traffic patterns and addresses demands where the UAM vehicles have the option to travel to a neighboring city. Since these results cannot be easily predicted because of the random variables, Monte Carlo simulations provide valuable insight and enable a view into the future. Different scenarios are presented, and their effects are analyzed. Based on the results, predictions of possible travel patterns and numbers of addresses that need to be allocated to each local city will be suggested. The presented scenarios are assessed and compared from multiple viewpoints including their dependence on demographics and lifestyle. The analysis can be expanded for cases with multiple cities. The start time for the simulations is set to 5 a.m. and a 30-minute observation window is selected for the simulations [12]. The conducted simulations show the approximate number of ICAO addresses needed for each area to accommodate the maximum number of UAM vehicles. Three different scenarios have been introduced, studied, and compared.

4.2 Analysis Scenarios

As the starting point, two cities/areas with a known number of UAM vehicles have been assumed. The first city has 15000 (N_1 in appendix) and the second city has 5000 (N_2 in appendix) UAM vehicles. Based on the assumptions explained in the appendix, UAM vehicles will be able to make inter-city and intra-city travels. For simplicity, as shown, each city has been divided into three sections: the UAM vehicles that request addresses for traveling intra-city (Staying), UAM vehicles that are requesting addresses to leave either of the cities (Leaving), and the ones that arrive in either of the cities (Incoming). Leaving and Incoming groups are divided into two sections each: Leaving UAM vehicles that (a) want to leave their own city (L_{12}, L_{21}) and (b) want to leave the neighboring city to go back to their own city (L_{11}, L_{22}); Incoming UAM vehicles that: (a) are arriving in the neighboring city (In_{12}, In_{21}) and (b) have left the neighboring city and are arriving to their own city (In_{11}, In_{22}). L_{12}, L_{21}, L_{11}, L_{22}, In_{12}, In_{21}, In_{11}, and In_{22} are each indicating a group of UAM vehicles as shown in the appendix. Each group is the product of the total number of vehicles in each city (N_1 and N_2), request probability (P_R), and the probability of staying (P_S) or leaving (P_L) or incoming (P_{In}) vehicles.

Furthermore, Table 1 shows the percentage of the UAM vehicles along with their requested flight duration for the Staying and Leaving groups. It is assumed that city 1 is larger compared to city 2 and the majority of the vehicles are traveling for work from city 2 to city 1. Additionally, it is assumed that the two cities are close to each other and cannot use the same set of ICAO addresses. In other words, since the UAM vehicles are able to travel between the two cities, those cities have different sets of available ICAO addresses. Due to the unavailability of the real data for the UAM vehicles, the assumptions used to generate the simulation results are assumed by the authors. However, any other sets of assumptions or real data can also be used in the proposed simulation tool. Three different scenarios are analyzed, and their results are compared in this paper.

Table 1 Percentage of UAM vehicles and their requested flight duration

Staying Vehicles		**Leaving Vehicles (city 2)**		**Leaving Vehicles (city 1)**	
Time Allocation (percentage)	Flight Duration (min)	Time Allocation (percentage)	Flight Duration (min)	Time Allocation (percentage)	Flight Duration (min)
30	60	5	120	15	120
20	90	5	180	15	150
15	120	10	300	30	180
10	150	25	540	40	300
5	180	25	600		
20	300	30	660		

4.2.1 UAM Vehicles Release their Addresses While Entering the Neighboring City (Scenario A)

The first scenario observes a case where the UAM vehicles release their addresses at the border of the two cities while entering the other city. In this case, the inter-city travelers request a new address from the city they intend to enter and will be assigned a new ICAO address. These vehicles are the incomers for the city they have arrived in, and they are added to this city's demand profile, while being subtracted from the demand profile of the city they departed. When the inter-city traveler's trip time to the neighboring city ends, they leave that city to their own area and, therefore, are subtracted from the demand profile of that city and again be added to their own city's demand profile. This process can be understood from the viewgraph in the appendix. The new demand profiles in the process and the Monte-Carlo-based simulation results which show the active number of UAM vehicles throughout the day are shown in Fig. 1.

Fig. 1 shows the process of inter-city and intra-city travels for both areas based on the assumptions presented in the appendix. The yellow dotted lines in Fig. 1.a and Fig. 1.c are representing the demand profiles of city 1 and city 2, respectively, where no inter-city travels are taking place. The red lines in Fig. 1.a and Fig. 1.c show the demand profiles for the UAM vehicles staying in city 1 and city 2, respectively, and the red lines in Fig. 1.b and Fig. 1.d show the demand profiles for the vehicles leaving city 1 and city 2, respectively. As shown in Fig. 1.d, the UAM vehicles start to travel to city 1 from 5:00 am to 8:00 am (L_{21}). Therefore, these vehicles are being subtracted from the initial demand profile of city 2 (shown in Fig. 1.c) and are being added to the initial demand profile of city 1 (In_{21}). Furthermore, starting from 11:00 am through 6:00 pm, the UAM vehicles of city 1 start to travel to city 2 (L_{12}) and these vehicles are subtracted from city 1's demand profile (shown in Fig. 1.a) and are being added to city 2's demand profile (In_{12}). Starting from 3:00 pm through 10:00 pm, the vehicles who were as guests in city 2 leave that city (L_{11}) to their own area (In_{11}). On the other hand, from 3:00 pm through 6:00 pm, the guest vehicles leave city 1 (L_{22}) to their own area (In_{22}). Therefore, the new demand profiles are deviating from the initial ones. Starting from 10:00 pm through 5:00 am, the initial and new demand profiles for both cities agree as there are no inter-city travels. Equation 1 explains the whole process regarding Scenario (A) and, according to this equation, the procedure can be extended to more than two cities. D_1 and D_2 show the new demand profiles for city 1 and city 2, respectively. As shown, the inter-city travelers affect both their own and the neighboring city's new demand profiles.

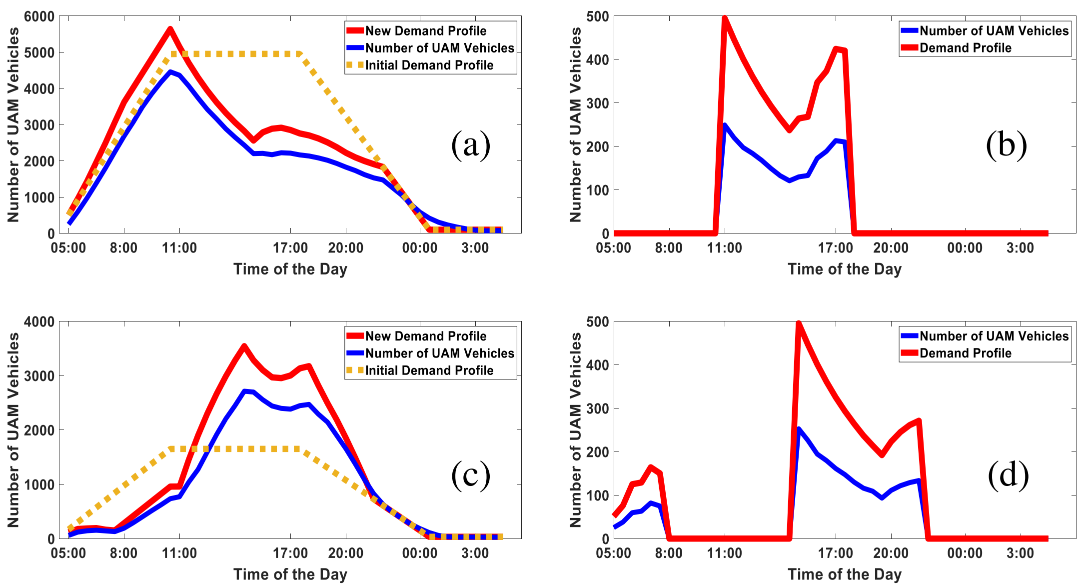


Fig. 1 Demand profiles and number of UAM vehicles through the day for (a): Staying vehicles in city 1; (b): Leaving vehicles in city 1; (c): Staying vehicles in city 2; (d): Leaving vehicles in city 2

$$\begin{bmatrix} P_{s1} - P_{L12} + P_{In11} & P_{In21} - P_{L22} \\ P_{In12} - P_{L11} & P_{s2} - P_{L21} + P_{In22} \end{bmatrix} \begin{bmatrix} P_R & 0 \\ 0 & P_R \end{bmatrix} \begin{bmatrix} N_1 \\ N_2 \end{bmatrix} = \begin{bmatrix} D_1 \\ D_2 \end{bmatrix} \quad (1)$$

Additionally, in order to prove the conservation of the number of cars in this case, the four new demand profiles shown with red lines in Fig. 1 have been added and compared with the sum of the two initial demand profiles shown in yellow dotted lines in Fig. 1.a and Fig. 1.c. As shown in Fig. 2, these two numbers completely agree throughout the day which proves that in the process of cars traveling to the neighboring city and coming back, the total number of cars has remained the same and proves the accuracy of the system. Moreover, the Monte Carlo simulation result showing the number of UAM vehicles throughout the day considering the demand profiles shown in Fig. 2, is also depicted in Fig. 2 in blue line. The maximum of this line, which is 5405, shows the approximate number of ICAO addresses needed for the whole process in Scenario (A).

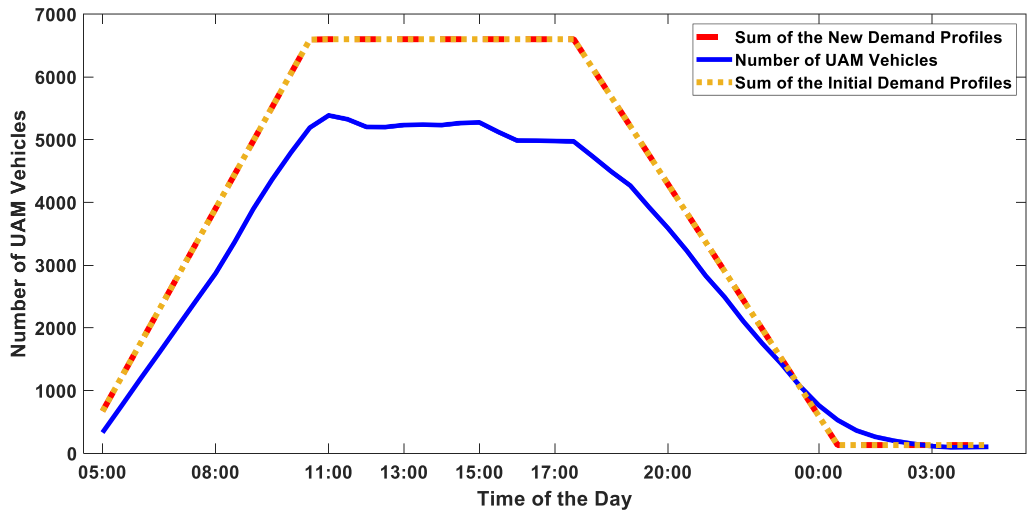


Fig. 2 Demand profiles and the number of UAM vehicles throughout the day (Scenario A).

4.2.2 UAM Vehicles Keep their Addresses While Entering the Neighboring City (Scenario B)

The second scenario observes a case where, unlike the first case, the UAM vehicles keep their addresses while entering the neighboring city. In other words, each UAM vehicle that initiates a leave for traveling to a neighboring city is assigned an ICAO address from its own city for the entire process. Unlike the previous case, the inter-city travelers do not affect the demand profile of the neighboring city, as they do not request an address from the neighboring city's ICAO address pool. However, when the inter-city travelers leave their own city, they will be subtracted from their own city's demand profile as they are not present there anymore and are not counted as a potential address requester. The new demand profiles throughout the day in the process and the Monte-Carlo-based simulation results which show the active number of UAM vehicles throughout the day are shown in Fig. 3.

Fig. 3 shows the process of inter-city and intra-city trips for both cities based on the assumptions presented in the appendix. The red lines in Fig. 3.a and Fig. 3.c show the demand profiles for the UAM vehicles staying in city 1 and city 2, respectively, and the red lines in Fig. 1.b and Fig. 1.d show the demand profiles for the vehicles who intend to leave city 1 and city 2, respectively. The yellow dotted lines in Fig. 3.a and Fig. 3.c show the initial demand profile where no inter-city travels are taking place and all the trips are inside a single city. As shown in Fig. 1.d, the UAM vehicles start to travel to city 1 from 5:00 am to 8:00 am (L_{21}). Therefore, these vehicles are being subtracted from the initial demand profile of city 2 (shown in Fig. 3.c), but unlike the previous case, they are not added to city 1's demand profile as they keep their addresses and are not counted as potential address requesters in city 1.

Furthermore, starting from 11:00 am through 6:00 pm, the UAM vehicles of city 1 start to travel to city 2 (L_{12}), and these vehicles are subtracted from city 1's demand profile (shown in Fig. 1.a). However, they are not added to city 2's demand profile. Starting from 3:00 pm through 10:00 pm, the vehicles who were as guests in city 2, leave this city to their own area (city 1) and are added to their own city's demand profile (In_{11}). Also, from 3:00 pm through 6:00 pm, the guest vehicles leave city 1 to their own location (city 2) and are added to their own city's demand profile (In_{22}). Starting from 6:00 pm for city 2 and 10:00 pm for city 1, all the inter-city travels are completed and there is an agreement between the initial and new demand profiles in Fig. 3.a and Fig. 3.c. Moreover, similar to the first case, equation (2) demonstrates the process with Scenario

(B). As shown, the inter-city travelers only affect their own city's new demand profile and do not have any effects on the neighboring city's new demand profile.

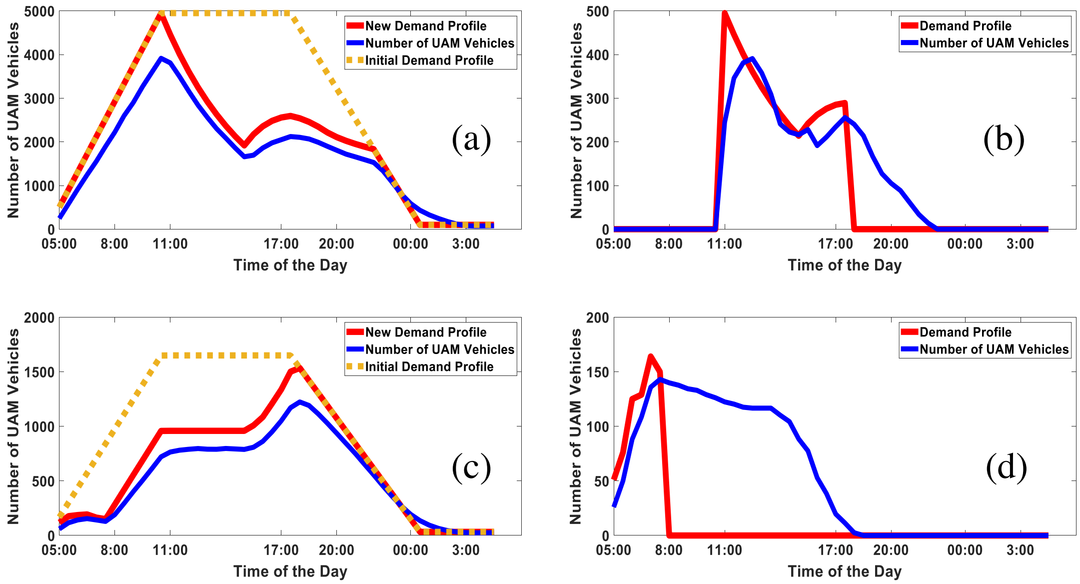


Fig. 3 Demand profiles and number of UAM vehicles through the day for (a): Staying vehicles in city 1; (b): Leaving vehicles in city 1; (c): Staying vehicles in city 2; (d): Leaving vehicles in city 2

$$\begin{bmatrix} P_{s1} - P_{L12} + P_{In11} & 0 \\ 0 & P_{s2} - P_{L21} + P_{In22} \end{bmatrix} \begin{bmatrix} P_R & 0 \\ 0 & P_R \end{bmatrix} \begin{bmatrix} N_1 \\ N_2 \end{bmatrix} = \begin{bmatrix} D_1 \\ D_2 \end{bmatrix} \quad (2)$$

Additionally, in order to prove the conservation of the number of cars for this case, the four new demand profiles shown in red lines in Fig. 3 are added. This task is performed considering that the UAM vehicles that have already left their own city, are not being considered in any of the stay/leave demand profiles as potential address requesters but are counted when calculating the total number of addresses needed. The added value is then compared with the sum of the two initial demand profiles shown in yellow dotted lines in Fig. 3.a and Fig. 3.c. As shown in Fig. 4, they completely agree through the 24 hours of the day which proves that in the process of cars traveling to the neighboring city and coming back, the total number of cars remained the same. Moreover, the Monte Carlo simulation result showing the number of UAM vehicles throughout the day considering the demand profiles in Fig. 4, is also depicted in Fig. 4 in blue line. The maximum of this line, which is 5747, shows the approximate number of ICAO addresses needed for the whole process in Scenario (B).

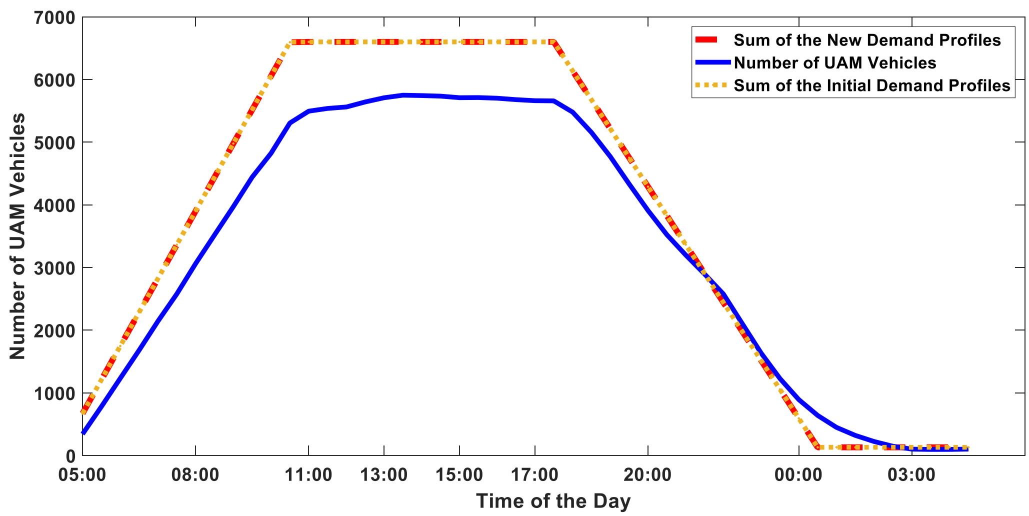


Fig. 4 Demand profiles and the number of UAM vehicles throughout the day (Scenario B).

4.2.3 Inter-city Travelers Choose an Address from a Shared Pool (Scenario C)

The third scenario observes a case where the inter-city travelers use a shared address pool to request an address. In other words, each UAM vehicle that initiates a leave for traveling to a neighboring city is assigned an ICAO address from a single shared address pool. This shared pool, for those intending to leave either city 1 or city 2, is generated by subtracting a percentage of the addresses allocated for the leaving vehicles in each city and adding them together. Hence, the demand profile for the inter-city travelers is created from the addition of the two city's Leaving demand profile (Fig. 5.b and Fig. 5.d). Therefore, as shown in Fig. 5, the inter-city travelers do not affect the demand profile of the neighboring city, as they do not request an address from the neighboring city's ICAO address pool. The new demand profiles throughout the day in the process and the Monte-Carlo-based simulation results, which show the active number of UAM vehicles throughout the day, are shown in Fig. 5.

Fig. 5 shows the process of inter-city and intra-city travel for both cities based on the assumptions presented in the appendix. The red lines in Fig. 5.a and Fig. 5.c show the demand profiles for the UAM vehicles staying in city 1 and city 2, respectively, and the red lines in Fig. 1.b and Fig. 1.d show the demand profiles for the vehicles who intend to leave city 1 and city 2, respectively. The yellow dotted lines in Fig. 3.a and Fig. 3.c show the initial demand profile where no inter-city travels are taking place and all the trips are inside a single city. As shown in Fig. 5.a and Fig. 5.b, the demand profile for the leaving vehicles is separated from the demand profile for those who request an address to stay, which is also true for city 2 (shown in Fig. 5.c and Fig. 5.d). In other words, inter-city and intra-city travelers have a separate pool of addresses and do not affect each other's demand profiles. As depicted in Fig. 5.a, other than the time between 11:00 am – 6:00 pm, where there are inter-city travelers from city 1, the initial and the new demand profiles agree for city 1. Similarly, as shown in Fig. 5.c, except for the time between 5:00 am – 8:00 am, the initial and new demand profiles agree for city 2. Moreover, similar to the previous cases, the process for Scenario (C) is also explained in a mathematical form in equation (3). D_{S1} and D_{S2} show the new demand profiles for staying vehicles in city 1 and city 2, respectively, and D_L shows the demand profile for leaving vehicles.

Additionally, in order to prove the conservation of the number of cars for this case, the four new demand profiles shown in red lines in Fig. 5 are added and compared with the sum of the two initial demand profiles shown in yellow dotted lines in Fig. 5.a and Fig. 5.c. As shown in Fig. 6, they completely agree throughout the day which proves that in the process of cars traveling to the neighboring city and coming back, the total number of cars remained the same. Moreover, the

Monte Carlo simulation result showing the number of UAM vehicles throughout the day considering the demand profiles shown in Fig. 6, is also depicted in Fig. 6 in blue. The maximum value of this line, which is 5725, shows the approximate number of ICAO addresses needed for the whole process in Scenario (C).

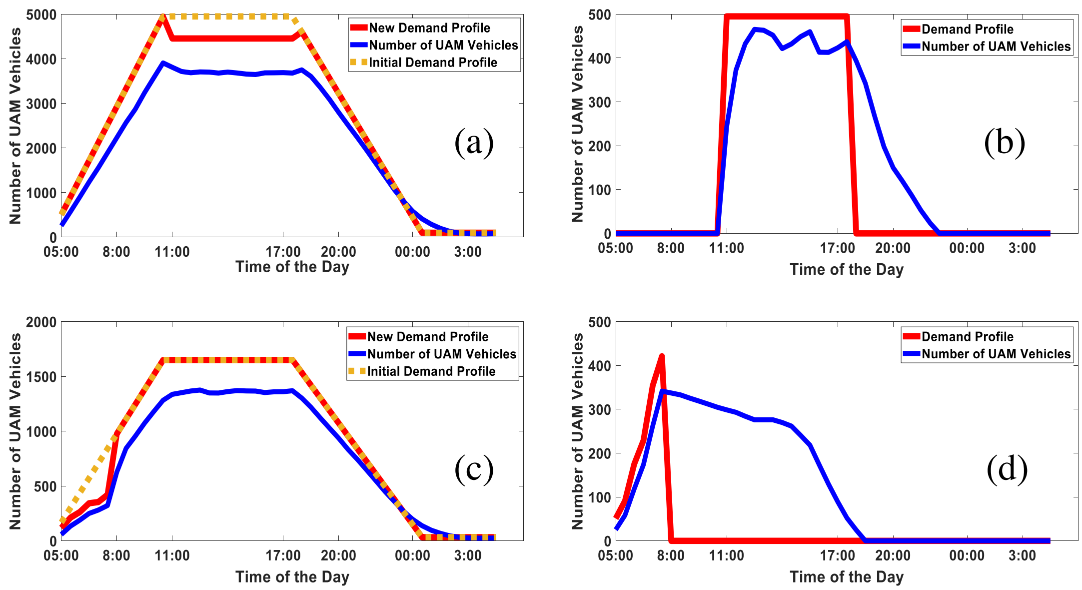


Fig. 5 Demand profiles and number of UAM vehicles through the day for (a): Staying vehicles in city 1; (b): Leaving vehicles in city 1; (c): Staying vehicles in city 2; (d): Leaving vehicles in city 2

$$\begin{bmatrix} P_{s1} & 0 \\ 0 & P_{s2} \\ P_{L12} & P_{L21} \end{bmatrix} \begin{bmatrix} P_R & 0 \\ 0 & P_R \end{bmatrix} \begin{bmatrix} N_1 \\ N_2 \end{bmatrix} = \begin{bmatrix} D_{s1} \\ D_{s2} \\ D_L \end{bmatrix} \quad (3)$$

4.3 Comparison Between Scenarios

In this section, a new concept, named License Hour, is introduced as

$$LH = \sum_{i=1}^{n} t_i \quad (4)$$

where n is the total number of requests for the staying or leaving vehicles for each city and t is the requested flight duration. In other words, LH is the total number of hours that the licenses are being occupied. According to this definition, it is clear that a large value of License Hour is indicative of better performance for the system, and it shows that a large portion of the available capacity of the system is being utilized and the redundancy is minimized. The value of License Hour for staying and leaving vehicles at each city for three different scenarios is shown in Table 2.

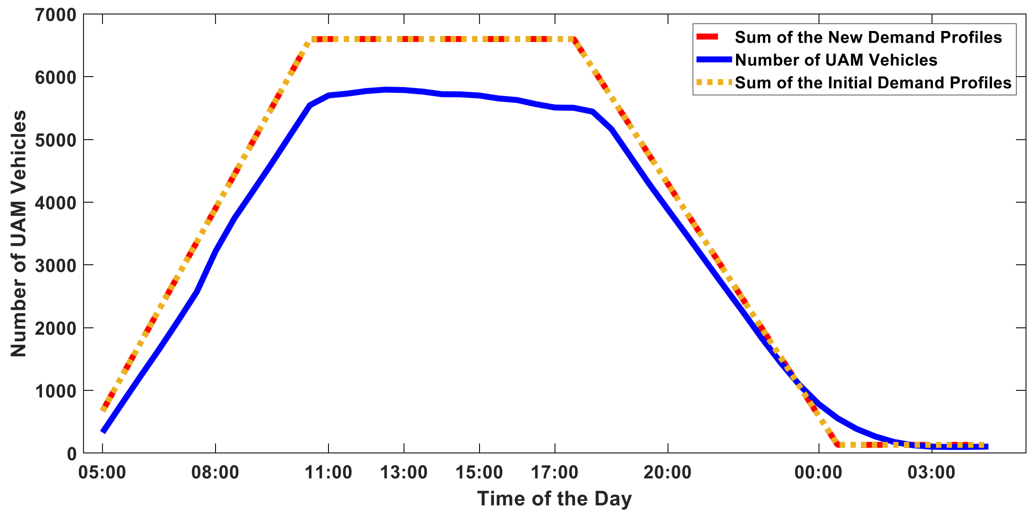


Fig. 6 Demand profiles and number of UAM vehicles throughout the day (Scenario C).

In order to compare the three scenarios, a new Figure of Merit (FoM) is defined. This figure is equal to the division of the sum of License Hour (LH) for each scenario by the maximum number of licenses needed for that case. Furthermore, a definition for the efficiency of each case is introduced as

$$\eta = \frac{\sum LH}{\int N_1 * P_R(t) + \int N_2 * P_R(t)} \tag{5}$$

where the two integrals in the denominator are evaluated over the entire 24 hours of the day, which demonstrates the area under the sum of the initial demand profiles. This area resembles a case where all of the UAM vehicles are using all the available addresses at each observation window throughout the day. This number is equal to 90,268 for all the cases. The calculated FoM and efficiency of each case are shown in Table 3.

Table 2 License Hour and total licenses required for each scenario.

	Staying (city 1)	**Leaving (city 1)**	**Staying (city 2)**	**Leaving (city 2)**	**Total LH**	**Total Licenses**
Scenario (A)	45,327	1225	24,180	1233	71,965	5405
Scenario (B)	40,163	2441	12,786	1280	56,670	5747
Scenario (C)	53,415	3756	18,235	3045	78,451	5725

Table 3 Figure of Merit and Efficiency for each scenario.

	Scenario (A)	**Scenario (B)**	**Scenario (C)**
Figure of Merit	13.3	9.9	13.7
Efficiency	80 %	63%	87%

As shown in Table 3, Scenario (C) and Scenario (B) have the highest and lowest efficiency, respectively. Additionally, Scenario (B) and Scenario (C) need a larger number of addresses compared to scenario (A), which is considered as an advantage for the first scenario as a smaller number of addresses is required to accommodate the requests throughout the process. Overall, Scenario (C) has the highest efficiency and FoM, which makes it the best scenario to be implemented while observing the cases from these two points of view. Moreover, Scenario (A) is harder to implement compared to the other two scenarios. Therefore, each scenario has its own advantages and drawbacks. This will be the air traffic management section’s responsibility to observe the situation and select a scenario over the other ones.

4.4 Conclusion

In this section, three different scenarios were introduced to observe the cases where the UAM vehicles were able to make both inter-city and intra-city trips. The three scenarios were focused on inter-city cases and consist of cases where the inter-city travelers (1) release their address at the border, (2) keep their addresses while crossing the border, and (3) use a shared address pool. The developed analysis tool using the Monte-Carlo simulation technique predicted the results and the outcomes of the three scenarios were compared using the introduced figures of merit. According to the observations, each scenario has its own advantages and possible limitations. Based on the situation, the air traffic management can examine the options and develop the most suitable policy.

4.5 References

[1] Holden, J., and Goel, N., "Fast-Forwarding to a Future of On-Demand, Urban Air Transportation," Uber Elevate, Uber White Paper, San Francisco, CA, Oct. 2016.

[2] Moore, M., Goodrich, K., Viken, J., Smith, J., Fredericks, B., Trani, T., Barraclough, J., German, B., and Patterson, M., "High Speed Mobility through On-Demand Aviation," Aviation Technology, Integration, and Operations Conference, AIAA Paper 2013- 4373, 2013.
https://doi.org/10.2514/6.2013-4373

[3] Mueller, E., Kopardekar, P., and Goodrich, K., "Enabling Airspace Integration for High-Density On-Demand Mobility Operations," 17th AIAA Aviation Technology, Integration, and Operations Conference, AIAA Aviation Forum, AIAA Paper 2017-3086, 2017.
https://doi.org/10.2514/6.2017-3086

[4] Moore, M., "Concept of Operations for Highly Autonomous Electric Zip Aviation," 12th Aviation Technology, Integration and Operations (ATIO) Conference, AIAA Paper 2012-5472, 2012.
https://doi.org/10.2514/6.2012-5472

[5] Patterson, M., German, B., and Moore, M., "Performance Analysis and Design of On-Demand Electric Aircraft Concepts," 12th Aviation Technology, Integration and Operations (ATIO) Conference, AIAA Paper 2012-5474, 2012.
https://doi.org/10.2514/6.2012-5474

[6] Smith, J., Viken, J., Guerreiro, N., Dollyhigh, S., Fenbert, J., Hartman, C., Kwa, T., and Moore, M., "Projected Demand and Potential Impacts to the National Airspace System of Autonomous, Electric, On-Demand Small Aircraft," 12th Aviation Technology, Integration and Operations (ATIO) Conference, AIAA Paper 2012-5595, 2012.
https://doi.org/10.2514/6.2012-5595

[7] Vascik, P. D., and Hansman, R. J., "Systems-Level Analysis of on Demand Mobility for Aviation," International Center for Air Transportation (ICAT) Rept. ICAT-2017-02, Massachusetts Institute of Technology, Cambridge, MA, Feb. 2017.

[8] Salleh, M., Tan, D. Y., Koh, C. H., and Low, K. H., "Preliminary Concept of Operations (ConOps) for Traffic Management of Unmanned Aircraft Systems (TM-UAS) in Urban Environment," Infotech@Aerospace, AIAA Paper 2017-0223, 2017.
https://doi.org/10.2514/6.2017-0223

[9] Holmes, B., Parker, R., Stanley, D., McHugh, P., Garrow, L., Masson, P., and Olcott, J., "NASA Strategic Framework for On- Demand Air Mobility," NASA NNL13AA08B, Hampton, VA, Jan. 2017.

[10] Duan, P., and Rankin, J., “ADS-B Feasibility Study for Commercial Space Flight Operations,” 29th Digital Avionics Systems Conference, IEEE Publ., Piscataway, NJ, 2010, pp. 3.A.1-1–3.A.1-11.
https://doi.org/10.1109/DASC.2010.5655472

[11] Duan, P., and Rankin, J., “ADS-B Space-Oriented Message Set Design,” 2011 Integrated Communications, Navigation, and Surveillance Conference Proceedings, IEEE Publ., Piscataway, NJ, 2011, pp. O2-1–O2-12.
https://doi.org/10.1109/ICNSURV.2011.5935353

[12] Ghayouraneh, S., El-Ghazaly, S., and Rankin, J., “Dynamic Addressing for On-Demand Mobility,” 2018 Aviation Technology, Integration, and Operations Conference, AIAA Aviation Forum, AIAA Paper 2018-4152, 2018.
https://doi.org/10.2514/6.2018-4152

[13] Ghayouraneh, S., Rankin, J. M., and El-Ghazaly, S. M., “Practical Considerations in Traffic Flow Systems for ODM Vehicles,” 2019 Integrated Communications, Navigation and Surveillance Conference (ICNS), IEEE Publ., Piscataway, NJ, 2019, pp. 1–7.
https://doi.org/10.1109/ICNSURV.2019.8735402

[14] Ghayouraneh, S., El-Ghazaly, S. M., and Rankin, J. M., “Investigation of Traffic Flow for ODM Vehicles in Dynamic ICAO Addressing Process,” AIAA Aviation Forum, AIAA Paper 2019-3627, 2019.
https://doi.org/10.2514/6.2019-3627

[15] Ghayouraneh, S., Rankin, J. M., and El-Ghazaly, S. M., “Dynamic Addressing for Urban Air Mobility Vehicles,” Journal of Air Transportation, Vol. 28, No. 4, 2020, pp. 1-4.
https://doi.org/10.2514/1.D0207

[16] Ghayouraneh, S., Rankin, J. M., and El-Ghazaly, S. M., “Monte Carlo Simulations to Predict Traffic Flow Patterns of UAM Vehicles,” Journal of Air Traffic Control, Vol. 62, No. 3, Nov. 2020, pp. 46-54.

Chapter 5

Conclusion

5.1 Conclusion

With the fast-growing population in large cities, the number of people using personal cars as the primary way of transportation is also increasing rapidly. Nowadays, especially in mega cities (e.g., San Francisco and Los Angeles), people are spending a minimum of 2 hours in traffic travelling to and from work. This unreasonable amount of wasted time has attracted the attentions to find out possible solutions in order to reduce the high traffic congestion in these cities. Urban Air Mobility is a recently introduced concept that is being considered as a fast and efficient way of urban transportation by switching a part of ground transportation to the air. Looking at the structure of the airspace defined by the Federal Aviation Administration, the design and airspace allocation for aircraft do not allow that much flexibility to other aviation-related transportation so as to be fitted into the defined airspace. The reason that Unmanned Aircraft Systems are now flying at or below 400 ft. with a minimum concern about collision risks is that this altitude is a part of airspace that is not being used for other manned aircraft. However, there are lots of challenges in defining the airspace such that the UAM vehicles can be fitted into. Possible altitude of operation for UAM vehicles is in the range of 1000-3000 ft., which certainly requires building a strong communication with the aircraft flying at the same level. This challenge of airspace equipage and air traffic management are among the biggest challenges of urban air mobility.

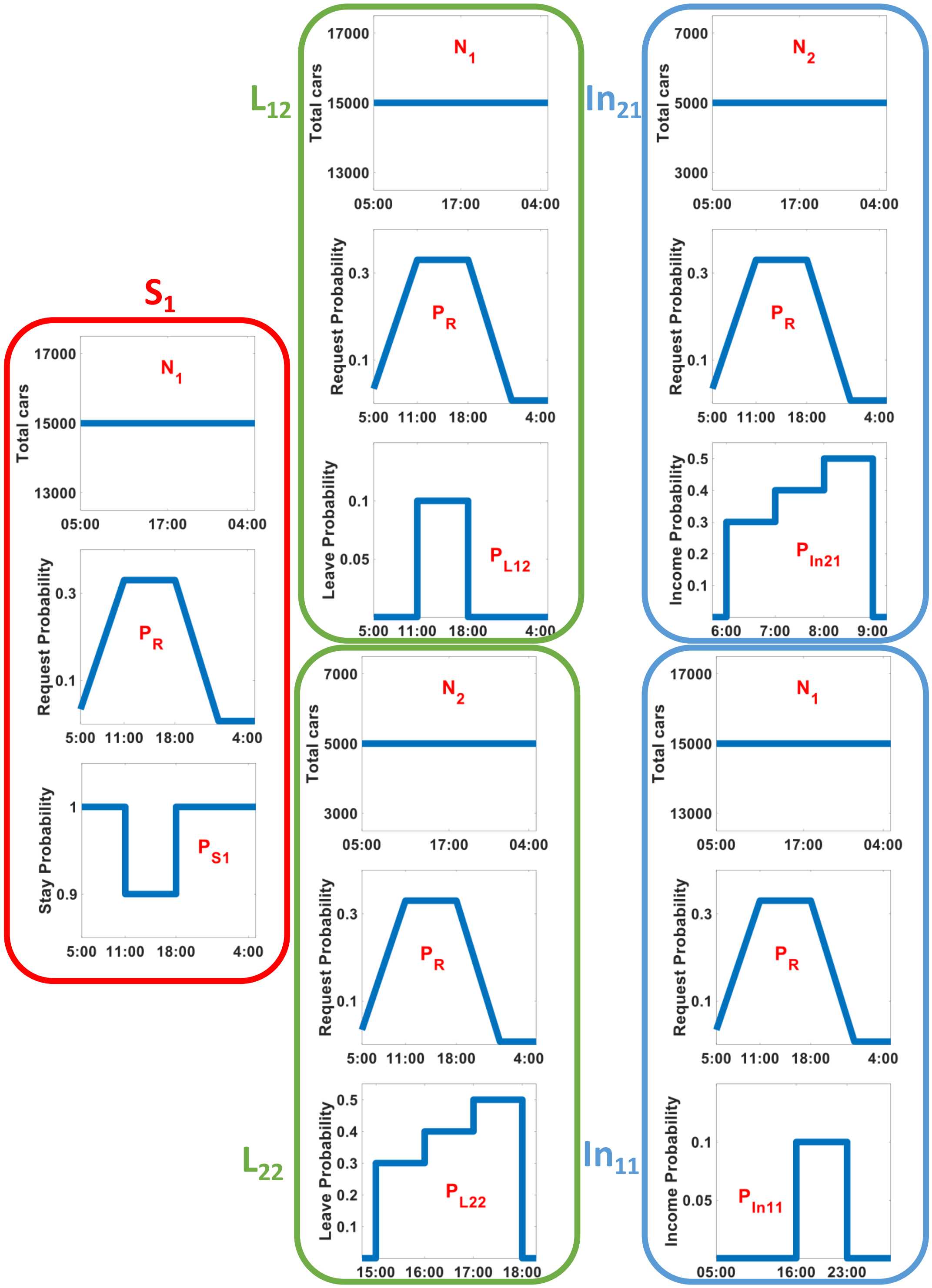
In Chapter 1, the usage of Automatic Dependent Surveillance-Broadcast systems for UAM vehicles was suggested as a potential way of making the air traffic management easier while different air vehicles are flying at different altitudes. Furthermore, in order to properly use the ADS-B system for the UAM vehicles, a need for a change in the message structure of an ADS-B message specially in the ICAO address field was discussed and dynamic ICAO addressing was introduced as a solution for the address scarcity problem of the UAM vehicles.

In Chapter 2, in order to simulate the traffic flow patterns of the UAM vehicles, a Monte-Carlo-based simulation tool was developed, and the simulation results were analyzed for two different cases with different sets of assumptions. The first set led to the proper observation window for the simulations and the second set explored a solution to determine the approximate number of ICAO addresses needed to accommodate the desired number of UAM vehicles which would be a solution for the address scarcity problem of the UAM vehicles.

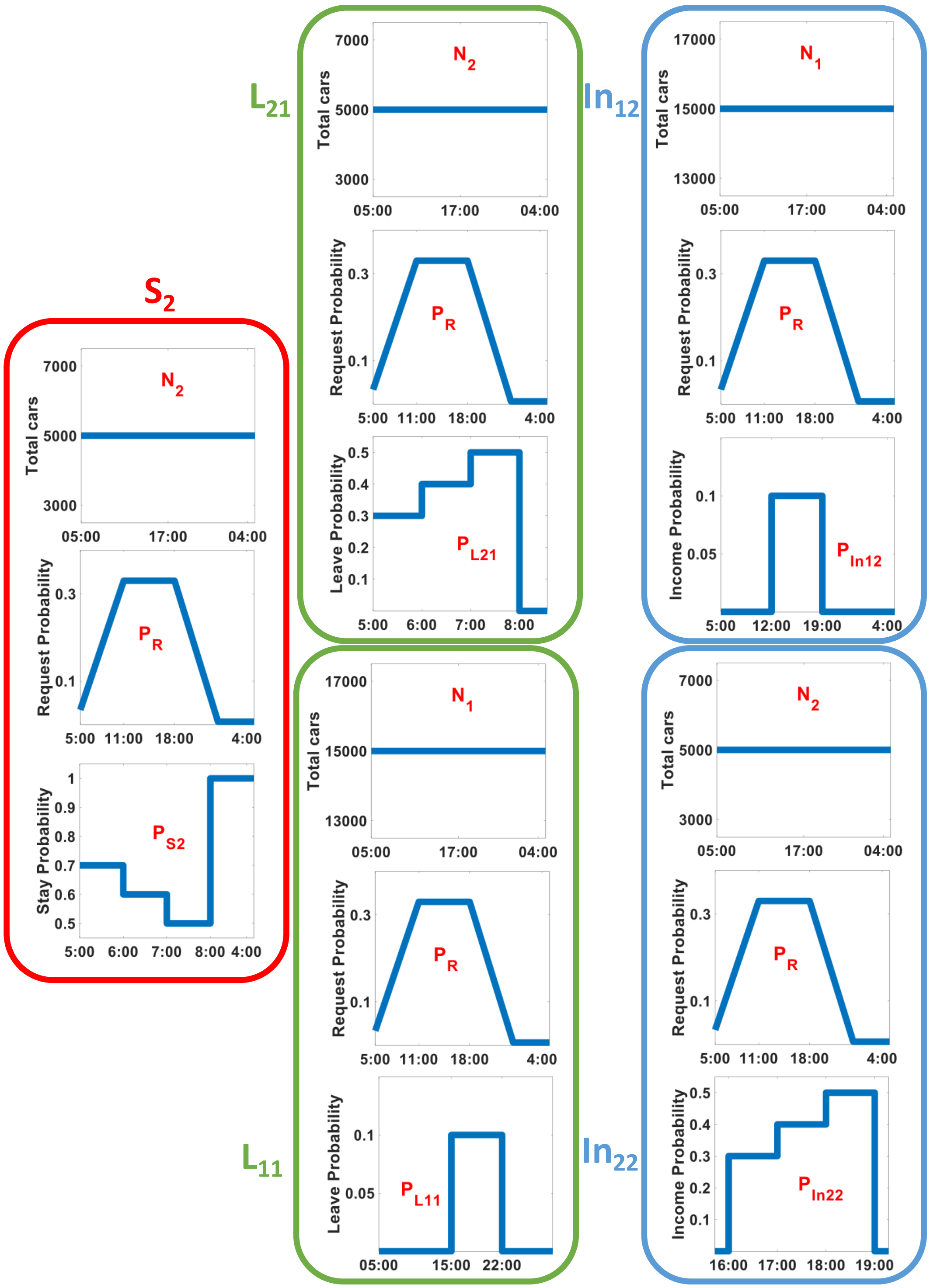
In Chapter 3, multiple scenarios of different policies and flexibilities and their impact on the distribution of the number of active UAM vehicles throughout the day were observed. Decreasing the maximum allowed flight duration in the busy periods of the day was proved to reduce the number of active UAM vehicles. Also, the effect of static and dynamic denials was observed and concluded that the static-denial approach alleviates the traffic faster, but the dynamic denial alternative is more fair, equitable, and adaptable as it offers the clients the option to be waitlisted. Overall, the dynamic-denial approach offered better customer service compared to the static one, and the price adjustment case was the most effective and flexible approach.

In Chapter 4, three different scenarios were introduced to observe the cases where the UAM vehicles were able to make both inter-city and intra-city trips. The three scenarios were focused on inter-city cases and consist of cases where the inter-city travelers (1) release their address at the border, (2) keep their addresses while crossing the border, and (3) use a shared address pool. The developed analysis tool using Monte-Carlo simulation technique predicted the results and the outcomes of the three scenarios were compared using the introduced figures of merit. According to the observations, each scenario had its own advantages and possible limitations. Based on the situation, the air traffic management can examine the options and develop the most suitable policy.

Appendix



S1
Total cars
N1
17000
15000
13000
05:00
17:00
04:00
Request Probability
PR
0.3
0.1
5:00
11:00
18:00
4:00
Stay Probability
PS1
1
0.9
5:00
11:00
18:00
4:00
L12
Total cars
N1
17000
15000
13000
05:00
17:00
04:00
Request Probability
PR
0.3
0.1
5:00
11:00
18:00
4:00
Leave Probability
PL12
0.1
0.05
5:00
11:00
18:00
4:00
In21
Total cars
N2
7000
5000
3000
05:00
17:00
04:00
Request Probability
PR
0.3
0.1
5:00
11:00
18:00
4:00
Income Probability
PIn21
0.5
0.4
0.3
0.2
0.1
6:00
7:00
8:00
9:00
L22
Total cars
N2
7000
5000
3000
05:00
17:00
04:00
Request Probability
PR
0.3
0.1
5:00
11:00
18:00
4:00
Leave Probability
PL22
0.5
0.4
0.3
0.2
0.1
15:00
16:00
17:00
18:00
In11
Total cars
N1
17000
15000
13000
05:00
17:00
04:00
Request Probability
PR
0.3
0.1
5:00
11:00
18:00
4:00
Income Probability
PIn11
0.1
0.05
05:00
16:00
23:00


S2
L21
In12
L11
In22
N2
N1
PR
PS2
PL21
PIn12
PL11
PIn22
Total cars
Request Probability
Stay Probability
Leave Probability
Income Probability