The fast pace of population growth is increasing traffic and gridlocks. Prior to the temporary work-from-home stipulations brought on by the COVID-19 pandemic, people wasted a notable amount of time in traffic while traveling to work, especially in larger cities. This valuable time could be used to grow economies at work or spent with family.\(^1\) Due to major traffic problems, mainly in congested cities, researchers are looking for a solution to solve this serious problem. Industry has introduced on-demand mobility (ODM) or UAM concepts to alleviate the traffic congestion by moving a part of urban transportation from the ground to the air.\(^2,\,3\)

Industry has widely discussed the importance of future urban air transportation and its challenges.\(^4\) This article outlines a broad view of future UAM services and describes different approaches and solutions for UAM-related traffic management.\(^4\) The authors used a Monte Carlo simulation technique to model the probability of different outcomes in a process that cannot be easily predicted due to random variables.

To be prepared for launching UAM, the structure of the airspace should be ready to accept operations of the new air vehicles.\(^6,\,11\) Although some of the challenges regarding the management of airspace for UAM vehicles are similar to other air vehicles such as UAS, UAM’s presence presents additional challenges.\(^1\) The altitude of operation for UAS is at 400 feet or less where no other air vehicle operates. Technologies like detect and avoid systems can be used to avoid collision,\(^12\) but as the UAM vehicles are categorized as manned vehicles and the operating altitude is 1,000 to 3,000 feet above ground level, traffic management becomes more challenging.\(^3\) To manage 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. However, for this system to be used in UAM vehicles, industry needs to make some modifications, especially to the message structure.

**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 used on either the 1090 megahertz (MHz) or 978 MHz frequencies. The 1090 MHz frequency is already so congested that it is unable to accept more clients, but the 978 MHz frequency is still a potential frequency for UAM-related communications. As a long-term solution, a frequency specifically assigned to UAM communications might be needed before the 978 MHz exceeds capacity. However, a third frequency would add complexity to any interoperability. Modifying the ADS-B message structure to fit the UAM concept is one major complexity.

An ADS-B message has 112 bits and 24 of those are allocated to the ICAO addressing field. For an aircraft registered in the US, the first four of the 24 bits are fixed to 1010 to represent that 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 percent of the available combinations are used, while the remaining 80 percent is reserved for future use. On the other hand, compare the number of available addresses for GA aircraft to the number of registered active cars and trucks in the US, which is about 264 million, and assuming that only one percent of these will be UAM vehicles, this number will exceed the number of available addresses.

The first solution is to change the structure of the ADS-B message to provide more addresses. However, it is not feasible to design a capacity-specific protocol that must be revisited or redesigned every time substantial growth occurs. The second solution is to use the remaining 80 percent of GA aircraft addresses for UAM vehicles. However, this is only a short-term solution because there aren’t enough addresses. The third solution is to use one of the three sets of four bits reserved for future use (1011, 1101, and 1111), specifically as the first four bits of the UAM vehicle’s ICAO address. This will open $2^{20}$ available combinations of addresses. However, this option still wouldn’t provide an adequate amount of addresses. The last solution is to use the dynamic ICAO addressing process.

This process is very similar to the Dynamic Host Configuration Protocol system where an Internet Protocol 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. The addresses will be assigned to the UAM vehicles dynamically, and the UAM vehicle will temporarily lease their addresses instead of owning them.

**Dynamic ICAO Addressing Process for UAM Vehicles**

With 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 can use any other unique numbering system. This request will be sent to an ATM-like system on the ground that has access to the pool of available ICAO addresses ($2^{20}$ number of addresses considering the first four 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. Dynamic addressing provides a greater number of unique addresses and since it is automatic, it minimizes possible errors.

Modeling new physical concepts uses various numerical and stochastic schemes. To simulate the case, a statistical approach based on a Monte Carlo technique was used. The Monte Carlo technique uses models to predict the likelihood of uncertainty behavior. 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 was assumed, but the developed analysis tool is independent of this number and can be scaled. Moreover, the simulation start time was assumed to be 5 a.m. and the traffic flow is studied throughout the day. In a previous study, traffic flow patterns were simulated at different observation windows throughout the day. The simulation
was conducted for four different observation windows (two hours, one 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 in this study. Simulations were 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, the average number of active vehicles throughout busy periods of the day was calculated to determine how many ICAO addresses to allocate to an area with a determined number of registered UAM vehicles. [25]

**Simulation Results**

To simulate the case, the authors considered two sets of assumptions based on real data. [25] Due to the unavailability of real data for the UAM operations, two data sets from the FAA for GA aircraft were used. However, it would be acceptable to use any other set of assumptions or real-case data. The first data set displays the busy and non-busy periods of the day in US airspace, which is illustrated in Figure 1. As shown, the number of active UAM vehicles increases starting from 5 through 11 a.m., it stays at its maximum through 6 p.m., when the number begins to decrease back to its minimum through midnight. This data demonstrates a pattern for the commercial flights in a 24-hour period, as well as a demand profile for UAM vehicles.

![Figure 1. Expected demand profile of the ICAO address requests throughout 24 hours.](image)

Figure 1. Expected demand profile of the ICAO address requests throughout 24 hours. [25]

Figure 2 provides information regarding the flight durations of a typical day, which was obtained from the FAA. Figure 2 also demonstrates the percentage of UAM vehicles versus their requested flight duration. For the simulations, the available flight durations were one hour, 1.5 hours, two hours, 2.5 hours, three hours, and five hours.

![Figure 2. Considered pattern for requested flight durations based on the percentage of the requests.](image)

Figure 2. Considered pattern for requested flight durations based on the percentage of the requests. [25]

In the first step, the simulation is conducted based on assumptions for a typical day. Figure 2 identifies available flight durations. As mentioned before, the developed analysis tool is completely independent of the assumptions. New data can be substituted whenever it’s available for the UAM operations. To study the traffic flow for this case, Figure 3 presents the Monte Carlo-based simulation results. [25-28]

![Figure 3. Number of active UAM vehicles throughout 24 hours.](image)

Figure 3. Number of active UAM vehicles throughout 24 hours. [25-28]

The blue line in Figure 3 represents the traffic flow or the distribution of the number of active UAM vehicles throughout the day under a maximum allowed flight duration of five hours. As represented in Figure 3, in the busy period of the day (11 a.m. to 6 p.m.) the number of active UAM vehicles is close to the maximum of the demand profile (5,000). Furthermore, Figure 4 shows a simulation has to study the average number of active vehicles throughout the busy period. This number could approximate how many ICAO addresses can accommodate the maximum number of UAM vehicles in an area. [25-28]

![Figure 4. Percentage of active UAM vehicles for 10 typical days.](image)

Figure 4. Percentage of active UAM vehicles for 10 typical days. [25-28]

As shown in Figure 4, the average number of active UAM vehicles in the busy period is about 82 percent. 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.

To alleviate the traffic in the high demand periods, multiple scenarios are provided to observe the effect of each case on the traffic flow pattern. These scenarios vary between 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. [25-28]

**Variation of the Maximum Allowed Flight Duration**

The first scenario shows the effect of decreasing the maximum allowed flight duration on the distribution of UAM vehicles in the
high demand periods. In this case, traffic flow was observed as the maximum allowed flight duration decreases from five hours to three hours. Available flight durations are one hour, 1.5 hours, two hours, 2.5 hours, and three hours. Figure 5 shows a decrease in active UAM vehicles after reducing the flight duration from five hours to three hours in the busy period. To calculate the approximate number of ICAO addresses needed to be allocated for this case, the average number of active UAM vehicles and their standard deviation were studied. As illustrated in Figure 6, the average number has decreased, which shows that decreasing the maximum allowed flight duration will reduce the number of active UAM vehicles in the high demand periods as well as the number of ICAO addresses needed.

In addition, a special case explores a situation in which the only available flight duration is one hour. This case is studied mostly for companies interested in last-mile deliveries but are limited by batteries. In this case, ICAO address will expire after one hour, when they will then be ready to be reassigned. As illustrated in Figure 9, limiting the available flight duration to one hour noticeably decreased the number of active UAM vehicles in the high demand period. Figure 10 shows a considerable decrease from about 82 percent for the five-hour flight case to less than 70 percent for this case. Furthermore, fewer active UAM vehicles in the busy period allows a larger number of address requests.

In this case, traffic flow was observed as the maximum allowed flight duration decreases from five hours to three hours. Available flight durations are one hour, 1.5 hours, two hours, 2.5 hours, and three hours. Figure 5 shows a decrease in active UAM vehicles after reducing the flight duration from five hours to three hours in the busy period. To calculate the approximate number of ICAO addresses needed to be allocated for this case, the average number of active UAM vehicles and their standard deviation were studied. As illustrated in Figure 6, the average number has decreased, which shows that decreasing the maximum allowed flight duration will reduce the number of active UAM vehicles in the high demand periods as well as the number of ICAO addresses needed.

To take it a step further, the effect of lowering the maximum allowed flight duration to two hours was studied. In this case, the available flight durations are one hour, 1.5 hours, and two hours. As depicted in Figure 7, the yellow line, which shows the traffic flow of the case with the maximum allowed flight duration of two hours, is less than the two previous cases in the busy period. This proves that decreasing the maximum allowed flight duration will alleviate traffic in higher demand periods. Figure 8 illustrates the average number of active UAM vehicles has decreased from about 82 percent for a maximum allowed flight duration of five hours to roughly 76 percent in a typical 10-day period. Reducing the maximum allowed flight duration in higher demand periods can allow the traffic management to accommodate a greater number of ICAO address requests.
Application of Static Request Denial

The second scenario shows a situation that tolerates a certain percentage of request denials. Defining the percentage of denials depends on the busy period’s situation. In this case, a tolerable number of requests will be denied, requiring clients to go through the requesting process again. The tolerable denial percentage is assumed to be 20 percent, but the developed analysis tool is completely independent of this number and can be scaled as needed. Figure 11 illustrates this case’s simulation results to observe traffic flow after denying a certain percentage of requests. As shown, there are fewer active UAM vehicles in the busy period than the case without any denials. Figure 12 illustrates the average number of active UAM vehicles for the case of denying 20 percent of the requests made throughout the high demand period. This average decreased from about 82 percent for a case without any denials to about 75 percent, 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 needed ICAO addresses.

Application of Dynamic Request Denial

The third scenario is similar in that limited addresses will force some request denials in the high demand period, but clients will not be greatly inconvenienced. However, unlike the previous case, 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. Figure 13 represents the traffic flow pattern while dynamically denying 20 percent of the requests in the busy period. Comparing Figures 11 and 13, which illustrate the traffic flow for the static and dynamic denials, respectively, show more 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. Figure 14 shows the average number of requests for the dynamic denial case in the busy period. Comparing this with the average number of active UAM vehicles for the case without any denials shows a slight decline from approximately 82 percent to about 79 percent. However, this decrease is not as significant as the static denial case, which alleviates traffic faster with the same denial percentages. However, in the dynamic denial case, clients have the option to be waitlisted instead of their requests being outright denied.

Figure 9. Number of active UAM vehicles throughout 24 hours.

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

Figure 11. Number of active UAM vehicles throughout 24 hours (maximum allowed flight duration is five hours).

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

Figure 13. Number of active UAM vehicles throughout 24 hours (maximum allowed flight duration is five hours).

Figure 14. Percentage of active UAM vehicles for 10 typical days (with dynamic denial).
**Application of Price Adjustment**

The fourth scenario studies applying price adjustments to the available flight durations – the longer the flight, the higher the hourly price. The price assignment starts from the beginning of the high demand period and stops at the end of it. As illustrated in Figure 15, the red line, which represents traffic flow for the price adjustment case, is considerably lower than the blue line associated with no price adjustments in the busy period. At the point that the price adjustment starts, the number of active UAM vehicles decreases, and when the price adjustment stops, the number of active UAM vehicles starts to increase, creating two peaks at both ends of the red line. Figure 16 shows the average number of active UAM vehicles for the case with price adjustments: it dropped from 82 percent for the case with no price adjustments to about 62 percent for this case. Applying price adjustments to flight durations and favoring shorter usage times alleviate traffic in the busy period and decreases the number of needed ICAO addresses. 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.

**Application of Modified Price Adjustment**

The final scenario is similar to the price adjustment case with some modifications. In this case, unlike the previous scenario, the price adjustment process will start two hours before the start time of the busy period and it will stop two hours after that period. Figures 17 and 18 show the simulation results associated with this case. In Figure 17, the yellow line showing the modified price adjustment case is smoother than the red line. Also, it does not have peaks at both ends which reduces the number of ICAO addresses needed. In other words, there is no need to consider the higher number of active UAM vehicles at the peaks which represent the start and the endpoints of the busy period. Furthermore, there are benefits for using this modified price adjustment because it generates revenue as it alters prices for the longer periods. Figure 18 also illustrates the average number of active UAM vehicles for the modified price adjustment case, which is slightly less than 60 percent. However, there is no need to consider the average number of UAM vehicles at the peaks for this case.

![Image](https://example.com/image1.png)

**Figure 15.** Number of active UAM vehicles throughout 24 hours (maximum allowed flight duration is five hours).

![Image](https://example.com/image2.png)

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

![Image](https://example.com/image3.png)

**Figure 17.** Number of active UAM vehicles throughout 24 hours (maximum allowed flight duration is five hours).

![Image](https://example.com/image4.png)

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

In this section, multiple scenarios and their impact on the distribution of active UAM vehicles throughout the day were observed. Decreasing the maximum allowed flight duration in the busy periods of the day reduced the number of active UAM vehicles. The effect of static and dynamic denials was observed and concluded that the static-denial approach alleviates traffic faster, but the dynamic denial alternative is more fair, equitable, and adaptable as it offers 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.
References:


