Risk Identification and Risk Assessment of Air Taxi Operations for Large-Scale Urban Air Mobility

Urban Air Mobility (UAM) is a developing concept in the aviation industry that promises to deliver safe, efficient, and accessible on-demand air transportation within a metropolitan area. In this paper, we identify and assess the hazards involved with this new, large-scale air transportation system. An on-demand air service, similar to ground on-demand transportation services, requires matching the customer location to the closest takeoff and landing area (TOLA) where they can travel in their reserved aircraft. Requirements for TOLA locations are that they need to be widespread and easily accessible within the metropolitan area, thus allowing the customer to onboard and offboard close to their destination. This novel concept requires creative air vehicle solutions to be developed for this unique mission profile, characterized by short/vertical takeoff and landing, short/medium-range cruise depending on the size of the metropolitan area, and small/medium payloads. The flexibility in mission design required by this novel concept can be achieved using electric air vehicles that will transport the customers to and from TOLAs, due to the recent advancements in battery technology and distributed electric propulsion (DEP). DEP allows more freedom in aircraft configuration design and can be used to accommodate a wider range of mission types. In particular, vertical takeoff and landing (VTOL), short takeoff and landing (STOL), and conventional takeoff and landing (CTOL) concepts are being explored in industry. It is crucial to identify and assess the impact of each challenge and prioritize risk mitigation planning, implementation, and progress monitoring early on to ensure that the issues that can hinder the successful implementation of a large-scale urban air mobility network are addressed. This paper will focus on identifying the hazards that will have the greatest impact on the air taxi industry. Then a risk assessment will be completed to identify the hazards that pose an extremely high risk to large-scale urban air mobility.

Keywords: urban air mobility, risk assessment

Introduction

Science fiction movies and cartoons have depicted the idea of flying cars as a futuristic transportation system, but can recent advancements in technology allow for urban air mobility (UAM) to become a viable option? Many visionaries forecast a future that holds a streamlined aerial vehicle network that can take individuals anywhere at any time [Zawodny]. Entrepreneurs, engineers, and government officials are working together to bring forward the concept, but are discovering hurdles that could threaten or wipe out this industry.

UAM promises to deliver safe, efficient, and accessible on-demand air transportation within a metropolitan area. In this paper, we identify and assess
the hazards involved with this new, large-scale air transportation system. On-demand air service will match the customer with the closest takeoff and landing area (TOLA). This novel concept requires creative air vehicle solutions to be developed for this unique mission profile, characterized by short/vertical takeoff and landing, short/medium-range cruise depending on the size of the metropolitan area, and small/medium payloads. The flexibility in mission design required by this novel concept can be achieved using electric air vehicles that will transport the customers to and from TOLAs, due to the recent advancements in battery technology and distributed electric propulsion (DEP). DEP allows more freedom in aircraft configuration design and can be used to accommodate a wider range of mission types. In particular, vertical takeoff and landing (VTOL), short takeoff and landing (STOL), and conventional takeoff and landing (CTOL) concepts are being explored in industry. It is crucial to identify and assess the impact of each challenge and prioritize risk mitigation planning, implementation, and progress monitoring early on. This will ensure that the issues that can hinder the successful implementation of a large-scale urban air mobility network are addressed.

It has been estimated that hundreds of vehicle concepts are being developed by established and emerging companies for UAM missions (National Academies of Sciences, Engineering, and Medicine 2020). There are several use cases for the UAM industry, but this paper will focus on the air taxi use case defined by the transportation of the passenger and luggage from point A to point B in an urban metropolitan area (Volocopter MediaCenter). It will be assumed that the aircraft is powered by a rechargeable battery in conjunction with an electric motor. This power option is the most likely to occur because it allows for flexibility in vehicle design by implementing DEP. A battery-powered aircraft is also more cost-efficient and environmentally friendly compared to a traditionally fueled aircraft. Also, the aircraft is assumed to be able to achieve vertical takeoff and landing. This will set the stage for the type of infrastructure that urban planners will be required to build to accommodate a large-scale air transportation model. Cities must prepare an environment to rapidly develop, test, and safely integrate this new technology. Safety is a top priority, so a detailed review of possible hazards can aid in diverting attention to risk mitigation planning.

This paper begins with a literature review identifying the hazards that will have the greatest impact on the air taxi industry. Methodology describing how a risk assessment matrix will be compiled to identify the hazards that pose an extremely high risk to large-scale urban air mobility will be presented. The results will present the assessment of the probability of occurrence and severity of impact for each identified hazard, then illustrate the risk assessment matrix to highlight the hazards that pose the highest level of risk. It will conclude with the final remarks.
Literature Review of Hazards

A risk assessment will be used to identify the issues that are most critical and require more attention. To achieve this, hazards must be identified and defined. The hazards that will be discussed in this paper are listed below:

- Noise Pollution
- Battery Technology
- Autonomous Technology
- Cybersecurity
- Public Approval
- Testing Grounds
- Regulations
- Weather
- Economics
- TOLAs

Hazards can be categorized by separating them into technical and non-technical groups. For example, a hazard that requires more engineering, research, and development will be categorized as a technical hazard. Hazards that require public education, paperwork, lobbying, and other forms of solutions will fall into the non-technical group. It should be noted that not all hazards are identified in this paper, but only those that appear to be widely discussed in the UAM industry.

Technical Hazards

Noise Pollution

Noise pollution in densely populated urban environments poses a serious threat to the UAM industry. Noise frequency and range contribute to the acoustic footprint of an aerial vehicle. The large noise footprint that will come with an increasing number of operating air taxis may dissuade communities from accepting UAM technology. So, it is vital to improve the design of the vehicle and reduce the noise that the public would classify as an annoyance. Currently, the industry is trying to address how to measure the acoustic footprint of small unmanned systems (sUAS) [Zawodny]. Note that all noise is not considered an annoyance by the public. High tip speeds contribute to tonal noise, which may be noise that can be perceived as an annoyance. However, another part of the noise footprint is known as broadband noise, which is the result of turbulent flow on or near the blade and can also pose a challenge for sUAS with multiple rotors [Zawodny]. Research to reduce noise for small UAVs is being carried out by both private and public sectors. Uber Elevate’s claims that a low disc loading, and low rotor tip speed will produce quieter aircraft (Uber). The combination of broadband and tonal noise must be assessed for each aircraft configuration to check if it can meet a publicly accepted standard for noise.
Battery Technology

A fully electric propulsive system provides a more cost-efficient and eco-friendly option over fossil fuel propulsion systems; however, battery-powered technology comes with limitations. Batteries are limited by their specific energy density and specific power density. Lithium polymer batteries are currently the key for all-electric aircraft (Courtin). However, this technology has posed thermal runway and energy storage problems (Courtin). Li-air batteries show promise in terms of potential for specific energy densities but require filters and storage tanks for the pure oxygen it requires to expend the battery’s energy (Ma). An additional cost to using non-aqueous Li-air batteries is the mass gain throughout the flight due to battery discharge (Ma). For large batteries, this weight gain can be significant, and adversely affect the aircraft performance of the weight-sensitive air taxis. Al-air batteries is another option for aviation applications, though it also comes with a drawback. Al-air batteries have major losses in capacity during recharging and might be more effective if recycled after use (Umeshbabu). It may require the addition of a recycling station to the takeoff and landing areas (TOLA). Al-air also results in mass gain during discharge, requires H2O to expend the batteries, and storage tanks to hold the H2O (Umeshbabu). The Li-S, a non-metal air option, has lower specific energy than the previously mentioned options, but still has a relatively high energy density compared to other batteries on the market. It uses Sulphur, an environmentally friendly and inexpensive material, which is also safer to handle (Umeshbabu). Although battery technology has proven to be capable and effective, research and development must continue to take place to make it a more viable option for this type of air taxi mission.

Autonomous Technology

Current software for autonomous operation is not mature enough for large scale UAM applications and produces challenges in communications and navigation. A typical approach to developing software allows room for error and bugs that are addressed with patches after the software is released for use, but this process will not work for this use case. It is vital, to begin with a set of requirements that will ensure a safe software system (National Academies of Sciences, Engineering, and Medicine 2020). The software programmed will be used for integrated air traffic management, collision avoidance, contingency management, weather, and wind pattern updates (National Academies of Sciences, Engineering, and Medicine 2020). Integrated air traffic management refers to the UAM network communicating to local air traffic controllers of all the operating vehicles that are in its class, owners of each vehicle, the current location of each vehicle, and route of each vehicle in real-time. Multiple classes of air vehicle traffic must be integrated within one network for the successful long-term large scale UAM system to function (National Academies of Sciences, Engineering, and Medicine 2020). Collision avoidance, an issue that will require a detect-and-avoid software to be installed on each air taxi, must be able to autonomously navigate the aircraft. Underestimated threats include collisions with birds or other unregistered drones with the purpose to harm.
The system must be able to detect-and-avoid such threats. Next, contingency management software is required to aid in cases of a communications system outage, other electronic system outages, or network breach. Changing weather and wind patterns also demand software applications to determine the best route for UAM operations. A complication for this application would be the need to develop advanced analysis tools to track wind patterns through a city’s profile, update it continuously, communicate it to the air taxi, and integrate it into the decision-making matrix of the autonomous software. Another point of interest is the type of safety engineering tools that must be developed to test software for a multivariable application of this magnitude (National Academies of Sciences, Engineering, and Medicine 2020). A combination of existing and emerging software will be required to ensure a safe system that can be used to navigate and communicate.

Cybersecurity

A software-heavy system that sends mission-critical information through wireless networks calls for a high level of cybersecurity. The loss of an aerial vehicle to adversaries due to lacking security can lead to a threat to national security, so securing the network to hundreds of drones poses a major hurdle to the success of a large scale UAM network (Javaid). Preventing the breach of onboard networks and code, attack on air traffic controldatalinks, the introduction of incorrect data in machine learning, or critical decision-making is of extreme importance (National Academies of Sciences, Engineering, and Medicine 2020). Modeling for UAM communication networks is challenging because it contains channels of different types, range of communication, different power requirements for different devices, multiple types of data flows, and varying integrity of equipment (Javaid). Therefore, establishing a system with high-security levels can be a challenging endeavor.

Non-Technical Hazards

Public Approval

A successful operation will depend on widespread public approval, which relies on educating the people about this new technology and eliminating misunderstandings. UAVs have had a bad reputation due to the on-board cameras often needed for navigation. The public is threatened by the possibility of abuse and infringement of their privacy rights as citizens. Public discussion about how video footage will be used should take place to relieve any hesitations that the city’s people may have about dozens of air taxis with cameras flying above them. Besides, the visual and noise pollution caused by a large network of air taxis may pose a problem in the early stages of development. Another public concern could be the usability of the air taxi services. Heavy public participation in testing can bring forth any unforeseen issues. For example, air taxis may not be accessible with people with disabilities and may need additional accommodations to include all members of the community. The perceived safety of the UAM system is another major
barrier. High safety ratings, testing, and public education may help ease
corns. The public must be a part of the discussions of acceptable levels of
noise and visual hindrances that the air taxis may contribute to. A public
opinion survey can be used as a way to periodically analyze public perception
throughout the development of the UAM industry, and assess the need for
discussion/education programs to be installed. It can be concluded that regular
communication must take place between the major players in the industry and
the general public to have a favorable outcome for all parties involved.

Testing Grounds
A high safety rating will be a top priority, which may require developing
more accessible testing grounds (National Academies of Sciences, Engineering,
and Medicine 2020). It has been discussed that there is a lack of low-risk
environments that can be used to test air taxi technology. Airspace and
facilities for new air vehicle design are needed for rapid design modifications
to develop. Typically, conventional aircraft design relies on a database of
historical data, but a database of data does not exist yet for this class of aircraft.
So, a low-risk testing environment will permit data gathering and promote safe
aircraft configurations, aircraft certification, and operating standards (National
Academies of Sciences, Engineering, and Medicine 2020). Improving the
perception of safety can show aid in the acceptance of this new technology.

Regulations
Gaps in the existing regulations may pose a threat to rapidly growing the
UAM industry. A thermal runway is a short circuit in batteries resulting in a
fire or combustion but can be regulated using containment systems (Courtin).
Although it is not considered a safety incident, current regulation still requires
a demonstration of a battery’s thermal runway, which can cause delays in the
certification of electric aerial vehicles (Courtin). For certain types of batteries,
identifying the amount of useful energy in a battery. Regulations may need to
be developed to monitor a battery’s history and accurately determine the
reserves before takeoff. There will be significant barriers to certifying
autonomous aircraft because it will require regulations for complex navigations
systems, sensors, and other previously discussed challenges. These gaps will
need to be addressed to assist in certifying all-electric autonomous vehicles that
will be used for UAM.

Weather
Weather is a non-technical challenge that will likely disrupt air taxi
operations. Adverse weather currently requires aircraft to be grounded, and
similar regulations will probably be implemented for the UAM industry.
However, if weather interrupts operations frequently, then it will cause
economic and passenger safety issues. This may also contribute to unfavorable
public opinion. Ideally, there is minimal adverse weather, low winds, no winter
weather, and moderate temperatures throughout the year (Goyal). Unfortunately,
this is not always the case in the majority of locations, and it can affect the
locations in which UAM will be able to operate in full capacity. For example, US urban areas in California, Arizona, and Texas will have more favorable weather year-round which is ideal for large scale development. Other cities may not be prioritized for adopting UAM technology due to weather constraints.

Economics

The economic feasibility of a UAM network is a topic of discussion for the public and private investors. Competition with existing modes of transport and emerging modes of transport such as fast trains, shared electric and autonomous cars will create a need for affordable UAM services (Goyal). Not only will air taxis have to be affordable for the average citizen, but also be able to adapt for new use cases. There is potential for UAM to expand into providing other services depending on the technology advancement timeline and demand. Some examples include providing aerial security for cities with high crime rates, transporting urgently needed medical items, or scientific research (Goyal). Adopting other use cases will make the UAM economically resilient and flexible, which will attract additional investors to this market.

TOLAs: Operation and Infrastructure

Takeoff and landing areas, TOLAs, used as the loading and unloading zone for air taxis need to be integrated with other transportation modes for an efficient solution. TOLAs are often envisioned as towers located in convenient locations throughout the urban area for UAM operations. However, the locations must be easily accessible by the public. Other transportation modes, such as autonomous automobiles, can be used to connect passengers from their current location to nearby TOLAs. A seamless system that integrates multiple transportation modes to the UAM network will be necessary for effective mobility. Another challenge for TOLA operation is the lack of oversight and policy, as the buildings will need to follow international fire and building codes, which may cause time delays and cost constraints. In addition, the security of TOLAs will also require attention during design and construction. If not, then the UAM will put the passengers, aerial vehicles, and communities at high risk. Passengers and visitor’s security screening will need to be time-efficient not to hinder operations, and the current airport model might not be a viable solution. Therefore, to operate an efficient UAM network, TOLAs must safely be able to host multiple air taxis, provide charging stations, and safe areas for passengers to wait in a high-security environment.

Methodology for Risk Assessment

Each hazard identified in the previous section is assessed in this section to determine the potential risks that will cause damage to a large scale UAM industry. Risk is defined as the possible loss in terms of probability and severity (Naval Safety Center). For example, parking in a busy grocery store
parking lot poses some risk of a car accident. Risk is lessened if the car is driven slowly, caution is exerted, and the car is parked farther away from the grocery store. Risk is increased if the car is surpassing the speed limit, without exerting caution, and parked in a spot with a lot of traffic. Risk is zero if the car is not driven at all. A risk assessment will allow the driver to select a safe parking spot that is at a reasonable distance from the entrance to the grocery store.

The following tables depict the scale that will be used to assess how often a hazard will occur and how severe the impact will be when it occurs. Table 1 illustrates the scale for the probability of occurrence that goes from frequent occurrence to unlikely occurrence, based on the FAA Probability Scale (Naval Safety Center). The risks are classified on a scale 0-100, divided into five different intervals, with range 81-100 rating a hazard that has probability to occur very often and 0-20 rating a hazard that is unexpected to occur.

Table 1. FAA Probability Scale

<table>
<thead>
<tr>
<th>Numerical Range</th>
<th>Scale</th>
<th>Probability</th>
<th>Define</th>
</tr>
</thead>
<tbody>
<tr>
<td>81-100</td>
<td>A</td>
<td>Frequent</td>
<td>Probably will occur very often</td>
</tr>
<tr>
<td>61-80</td>
<td>B</td>
<td>Likely</td>
<td>Probably will occur often</td>
</tr>
<tr>
<td>41-60</td>
<td>C</td>
<td>Occasional</td>
<td>Expected to occur occasionally</td>
</tr>
<tr>
<td>21-40</td>
<td>D</td>
<td>Seldom</td>
<td>Expected to occur on a rare basis</td>
</tr>
<tr>
<td>0-20</td>
<td>E</td>
<td>Unlikely</td>
<td>Unexpected, but might occur</td>
</tr>
</tbody>
</table>

Source: Naval Safety Center.

Table 2 illustrates the scale for the severity of impact if a hazard does occur, and ranges from catastrophic to negligible, based on the FAA Severity Scale (Naval Safety Center). The risks are classified on a scale 0-100, divided into four different intervals, with range 75-100 rating a hazard that has catastrophic potential outcomes and range 0-25 rating a hazard that creates negligible damage.

Table 2. FAA Severity Scale

<table>
<thead>
<tr>
<th>Numerical Range</th>
<th>Severity</th>
<th>Define</th>
</tr>
</thead>
<tbody>
<tr>
<td>75-100</td>
<td>Catastrophic</td>
<td>Loss of life; complete equipment loss</td>
</tr>
<tr>
<td>50-75</td>
<td>Critical</td>
<td>Accident level of injury and equipment damage</td>
</tr>
<tr>
<td>25-50</td>
<td>Moderate</td>
<td>Incident to minor accident damage</td>
</tr>
<tr>
<td>0-25</td>
<td>Negligible</td>
<td>Damage probably less than accident or incident levels</td>
</tr>
</tbody>
</table>

Source: Naval Safety Center.
The combination of the probability and severity scales can be used to assemble a risk assessment matrix as shown in Figure 1. The probability is rated from frequent to unlikely in the x-axis, while the severity is rated from negligible to catastrophic on the y-axis. The regions are split into four levels of risk: extremely high, high, medium, and low. The low-risk region includes hazards that have negligible, moderate, or critical severe probability with seldom or unlikely occurrence. The more frequent these hazards occur, the higher the risk level they will be placed in.

**Figure 1. Risk Assessment Matrix Example**

Once each hazard is assessed, the ones that pose an extremely high risk can be identified, and risk mitigation plans can be assembled for the hazards that threaten the greatest risk.

**Results and Discussion**

This section will assess each hazard by assigning a value for the probability and severity. First, the hazards are ranked based on their probability of occurrence, shown in Table 3, using the scale described in the previous section.

**Table 3. Probability of Occurrence**

<table>
<thead>
<tr>
<th>Hazard</th>
<th>Probability</th>
<th>Reasoning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noise Pollution</td>
<td>90</td>
<td>The presence of noise from rotors/fans is expected from all aircraft concepts.</td>
</tr>
<tr>
<td>Battery Technology</td>
<td>25</td>
<td>Catastrophic battery failure is expected to occur rarely.</td>
</tr>
<tr>
<td>Autonomous Technology</td>
<td>50</td>
<td>System failure is expected to occur occasionally.</td>
</tr>
</tbody>
</table>
Noise has the highest probability of occurring because almost all aircraft designs implement a propeller or rotor as a part of their electric propulsion system. The least probable hazards are interest in developing testing grounds and TOLAs. It is assumed that the infrastructure needed to operate is high and will be funded by public and private entities. Next, each hazard was assessed based on the severity of impact when it unfolds and is shown in Table 4 below.

Table 4. Severity of Impact

<table>
<thead>
<tr>
<th>Hazard</th>
<th>Severity</th>
<th>Reasoning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noise Pollution</td>
<td>45</td>
<td>It is unlikely that this will cause major issues as much research is being conducted to reduce noise to acceptable levels.</td>
</tr>
<tr>
<td>Battery Technology</td>
<td>85</td>
<td>Battery failure will result in catastrophic damages to the passenger, payload, and aircraft.</td>
</tr>
<tr>
<td>Autonomous Technology</td>
<td>75</td>
<td>Autonomous software development, testing, certification, and regulation will be challenging. Technology failure can cause significant damage to the aircraft, passenger, and/or public.</td>
</tr>
<tr>
<td>Cybersecurity</td>
<td>90</td>
<td>Cybersecurity breaches by an adverse party is a catastrophic event.</td>
</tr>
</tbody>
</table>
Public Approval | 25 | Public approval issues can be resolved through proper education and local community participation.
Testing Grounds | 60 | Inadequate testing facilities produce low technology confidence levels and may lead to critical failure.
Regulations | 60 | Delays in the timeline—threatens the feasibility of large scale UAM operations.
Weather | 35 | Weather patterns may be predicted but can lead to grounding all aircraft and pausing operations. May lead to economic losses and minor damages.
Economics | 20 | There are diverse use cases that this technology can be applied, which may forgo economic losses of investment in the air taxi industry.
TOLA | 30 | Minor damages may be caused if the TOLAs are managed poorly.

In Table 4, a software breach due to failure in cybersecurity has the potential to cause the most damage. The economic losses due to running an air-taxi are predicted to have the lowest severity. The reasoning behind this rating is that the technology developed using the investment can be used for other applications outside of the air taxi industry. Figures for both probability and severity were combined to produce the risk matrix in Figure 2.

**Figure 2. Risk Assessment Matrix**

This simplified risk assessment matrix was assembled based on a similar model described in the previous section. Note that the probability axis is reversed and reads 100 to 0 from left to right. This is based on the model risk matrix which reads from frequent to unlikely.

Risk levels include extremely high, high, medium, and low displayed in the main area of the matrix. The hazards in the high-risk category include noise...
pollution, regulations, autonomous technology, cybersecurity, and battery technology. Autonomous technology, cybersecurity, and battery technology occur seldomly or occasionally while having the potential for causing catastrophic damage. These hazards describe a situation where there is a total loss in control of the aircraft due to adversaries or spontaneous failure. The level of risk will remain the same unless there is a breakthrough in technology.

A timeline obstruction caused by regulatory guidelines is likely to occur and can cause critical damage to the industry. Entrepreneurs may lose interest if the government does not work to adapt to this new aviation sector. However, if the government is quick to establish a system to streamline the certification of air taxis, then the level of risk will decrease. Then there is the constant noise pollution that will be present and may cause some minor damage to public opinion and health. Research is being conducted to lower noise levels and may reduce the severity of this hazard. Weather poses a medium level risk and can move to a higher or lower risk level based on weather prediction technology development. Also, if the location of operation sees increasingly severe weather due to the global warming crisis, this hazard will pose a greater risk. Higher temperatures and extreme weather may require air taxis designs that are more resilient and adaptive for safe operation. Public approval, economics, TOLAs, and development of testing grounds all pose a low-level risk. The economic risk is low due to the diversification of use cases for UAM technology and is predicted to reduce the risk level of this hazard. Development of testing grounds and TOLA infrastructure are both unlikely to occur but can cause moderate or critical damage. These two risks may increase if there is a delay in development due to strict certification requirements or an increase in construction/labor costs. Public approval may occur more frequently than the other hazards in the low-risk level category, however, the damage is negligible if it is managed effectively. But this risk can dramatically increase to higher levels if it is not monitored or addressed regularly through educational programs. The level of risks for the identified hazards will vary based on the behaviors of the UAM industry over time.

Conclusions

UAM is an emerging idea in aviation pledging to provide safe, efficient, and accessible on-demand air transportation. The design solutions are expected to provide flexible electric air vehicles that will transport the customers to and from TOLAs. It is crucial to identify and assess risks in the UAM industry and prioritize risk mitigation planning, implementation, and progress monitoring early on to ensure successful implementation. The assessment in this paper illustrates the barriers that currently pose the highest level of risk. Which is, as highlighted in the previous section, noise pollution, regulations, autonomous technology, cybersecurity, and battery technology. It must be noted that this assessment was based on current market discussions, trends, and technology. A more detailed revaluation as the industry develops is necessary to effectively
mitigate risk. The next step would be to form risk mitigation plans for hazards with unacceptable levels of risk: high and extremely high risk. The level of planning allows the industry to operate safely and efficiently—which is crucial to the success of the UAM industry.

References


