

Concept Paper

Sustainable Urban Air Mobility Supported with Participatory Noise Sensing

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Abstract: In about 15 years, there is likely to be urban air mobility (UAM) in larger cities across the globe. Air taxis will provide on-demand transportation for individual needs. They will also connect important transportation nodes, such as airports and city centers, as well as providing quick transfers between train stations or a convenient option for crossing rivers and lakes. It is hoped that UAM will help meet today's political targets of sustainability and decarbonization. However, there are certain threats that could impede the sustainable and thus successful introduction of UAM to our cities, with noise being a prominent limitation. This paper argues that citizens have to be viewed as stakeholders in urban air transportation, regardless of whether they or not intend to use it, and that a concept of resident participatory noise sensing (PNS) will be beneficial to the implementation of UAM. Web-based services and smartphones facilitate the access and updating of current information about local noise distributions, thus enabling them to be used to foster UAM in smart cities.

Keywords: urban air mobility; transportation; air taxi; smartphone; acceptance; participatory noise sensing; noise annoyance

1. Introduction

Looking ahead, in about 15 years, there is likely to be urban air mobility (UAM) in larger cities across the globe. If economic predictions come true, thousands of air-taxi flights will take place in capital cities daily, not only in megacities. The potential benefits of UAM are an increase in e-mobility connected with a reduction of pollution from fossil-fuel emissions, as well as a reduction in travel times by avoiding congestion. This article is based on a paper presented at the 2019 World Wide Web Conference, May 2019 in San Francisco, CA [1]. Note that due to the increasing speed of development the time horizon to UAM realization has been reduced from 20 to 15 years.

Around the globe, authorities are trying to keep up with developments in this industry by publishing regulations at both national and international levels, and defining criteria for political planning. The European Commission, for instance, fosters UAM in order to ensure economic growth. The Horizon 2020 research program on smart, green and integrated transport identified two key criteria to achieve sustainable UAM: decreasing the overall environmental footprint, and controlling the noise and visual pollution [2] (p. 86).

Noise generated by UAM has been identified as a critical factor in this development. Even though initial reactions among residents to well-controlled urban flight trials have been neutral or even positive [3], there is likely to be opposition to the full-scale onset of UAM, when there are several thousand flights daily in a single city.

In 2004 the International Civil Aviation Organization (ICAO) came up with a document outlining a balanced approach [4], which aims to limit or reduce the number of people affected by significant aircraft noise. About 50 years after jet engines were introduced in commercial aviation, four elements

for noise management in the vicinity of airports were described: land-use planning, reduction in noise at source, noise abatement measures, and restrictions on aircraft operations as a last resort.

In an attempt to proactively regulate all aspects of upcoming Unmanned Aerial Operations, and “In order to facilitate the societal acceptance of UAS operations” [5] (p. 47), the European Commission has recently issued Implementation Regulations to be set into force July 2020. Noise limitations for unmanned aircraft operated close to people are announced: “To provide citizens with high level of environmental protection, it is necessary to limit the noise emissions to the greatest possible extent” [6] (p. 2). However, the Annex Part 15 to this document indicates a maximum allowable sound power level of 85 dB for drones in the ‘open’ category [6] (p. 40). This is comparable to the noise of an A320neo during standard takeoff with maximum takeoff weight [7] and thus in contradiction to any societal acceptance.

In the current state of initial planning for UAM operations, the experiences gained and technical developments achieved should make it possible to take the initiative necessary to make UAM socially accepted and sustainable from the very start. Care needs to be taken that using drones to transfer urban transportation into the vertical dimension does not simply reproduce old problems for the sake of finding new markets [8].

For this purpose, it is proposed to help raise acceptance for UAM and the noise associated with it among individual residents as well as communities by means of transparency. This concept views residents as stakeholders in UAM and widens the call for continuous noise measurements of vertical take-off and landing operations at individual sites [9] (p. 26), with data collected by residents voluntarily and enabled by smartphone-based participatory noise sensing.

Although the main objective, the argument and the conclusions are the same to my previous work [1]; in this article, the problem is depicted with much more detail. Besides taking into account the inherent conflict between recent WHO guidelines on noise and the new EU regulations, the article makes reference to the current health literature and relates to the most recent findings and trials on UAM acceptance. In addition, reference is made to wireless networks, crowdsourcing of environmental data, and the latest PNS research.

2. UAM Traffic Concepts

It is envisaged that air taxis will operate between dedicated locations in the city. Droneports (also called vertiports or skyports) will develop at various points in the city, allowing easy access and the opportunity to transfer to other modes of transportation, as well as technical support, such as battery charging and maintenance for air-taxi vehicles. Taking this into consideration—along with no-fly zones that are in place due to safety restrictions, e.g., above public buildings, correctional institutes, hospitals, and other specifically protected locations—it becomes apparent that the air space available for UAM will be quite limited.

A typical approach for aviation administrations is to bundle such routes in corridors to keep drone traffic separated from other airspace users (for a recent example see [10]). NASA also sees corridors (Special Flight Rules Area) or even the use of defined helicopter routes as potential concepts for emergent UAM operations [11]. Organizing UAM in a manner that is similar to today’s commercial air traffic, i.e., using certain corridors (or tubes, see [12]), is meant to guarantee safe operations. However, following this concept, the noise problem will not only exist in the vicinity of droneports, where vehicles take off and land, but also for citizens living or working below these corridors, which will be at an altitude between 500 and 1500 feet. Working or living under or near such a corridor will overly expose citizens to air-taxi noise emissions and could become a limiting factor for UAM: “One potential outcome of scaled-up drone operations is an increase in urban noise volume exceedances above legal or desired limits” [13] (p. 39). An expected decrease in the quality of life and/or real estate values due to UAM could lead to lawsuits and/or restrictions. Strong public opposition could finally become a showstopper for UAM, at least in Western megacities, which is also the reason why the aviation industry sees “involving community engagement now vitally important” [14] (p. 5).

3. UAM Acceptance

Currently, the usage of air taxis has only garnered limited acceptance among the public. In a representative study conducted in Germany in 2018 [15], 86% of the respondents in a telephone survey indicated they would not use air taxis. Moreover, even being positive about using UAM does not necessarily mean to accept it flying above the own dwelling: among the 14% of respondents who agreed either fully (4.9%) or slightly (9.2%) with the prospect of using unmanned air taxis, only two out of three would accept air taxi flying above their home during daytime, and less than half would agree to night-time flyovers [16].

In an online survey about UAM conducted in Germany in 2019 [17], 27% of the sample agreed to use air taxi services for traveling distances of up to 200 km between cities or from a city center to an airport. Own usage of air taxis in urban traffic and for commuting to and from work was agreed to by 20%. The support of UAM in general was about 9% higher for each of the different purposes, meaning that in this survey acceptance of UAM was provided by up to one third of the respondents.

Acceptance might be different in other parts of the world, for instance an international study [18] using online surveys reports 67% of respondents from Mexico City being likely or very likely to use UAM, with the comparable figures being 46% for Los Angeles, 32% for Switzerland, and 27% for New Zealand.

Until recently, such data were based on educated guesses about how UAM would look and sound, making any interpretation and comparison difficult. When spectators were able to gain real experience when viewing the first flight of an air taxi in a European city in September 2019, data were obtained. Participants in the field study (N = 1203) could not only see and hear the volocopter flying, but also take seat in the vehicle on ground in order to get familiar with this new type of mobility service. Asked whether they would use the air taxi in autonomous flight, 37.9% answered “most likely” and another 28.9% “likely”, which adds up to 67% overall acceptance [3].

Acceptance of air taxi usage by two thirds of this sample surely reflects local factors such as community engagement, political support, and traffic congestion experienced, and one can question whether or not these samples are representative. Typically, such high acceptance values have only been achieved for certain cities, not for whole countries.

In the 2018 telephone study cited above, participants had been asked to what extent they were concerned about different aspects of civil drone usage. Most of the respondents confirmed their concern about the possibility of misusing drones for criminal purposes (91%), followed by privacy concerns (86%). Concerns connected with mishaps all raised concerns in the range of 72% to 75%, followed closely by concerns about animal welfare. Concerns about noise were confirmed less frequently (53%) [15]. However, among all concerns, those relating to noise are the strongest predictor of acceptance of civil drones: people who are concerned about noise show least acceptance [19].

4. Noise Considerations

Among all sources of environmental noise, research has shown that the noise generated from aviation is the most annoying [20]. When different modes of transportation are assessed in combination, aviation noise is likely to define the level of annoyance [21]. In psychoacoustic tests, subjects rated the sound of drones as more annoying than that of road vehicles, at an equal level of sound pressure [22]. When investigating the effects of a drone noise from a small multicopter added to various audio-visual scenarios, [23] found in soundscapes with reduced traffic noise subjects in the position of a pedestrian reporting higher perceived loudness and annoyance compared to scenes highly impacted by road traffic noise, although the drone noise was held constant at 65 dBA across all scenarios. However, instead of seeing this as proof for the potential of masking drone noise using street traffic, the results rather underline the impairing aspects of drone noise on the residents of such roads: as traffic varies over the day there will be times with low traffic volume when local residents experience the loudness and annoyance of drones much more (“annoyance up to 6.4 times higher than without drone noise” [23] p. 18), e.g., at nighttime.

Thus, attempts such as hiding UAM noise by planning flight corridors above highways or major roads are questionable as long as any residents would be affected.

Similarly, there have been concepts to hide noise emissions from droneports by placing them in industrial zones or even highway cloverleaves [9]. However, the dilemma lies in the travel distance from the individual starting point of a journey to the droneport, making the speed and efficiency of the whole journey dependent on street traffic conditions. Vertiports need to be in the vicinity of people's destinations, making the UAM noise an issue again. Moreover, due to the additional power needed, the sound levels of urban air vehicles produced during vertical takeoff or landing are at least 10 dB above the corresponding levels during flyover. In terms of noise perception, such an increase is equivalent to doubling the noise, which will almost certainly result in conflicts with surrounding communities. For example, volocopter reports noise emissions of 65 dB(A) hovering at a distance of 75 m and 76 dB(A) at a distance of 30 m while landing [24].

4.1. Noise Annoyance

With its objective to protect human health and wellbeing, the World Health Organization (WHO, Geneva, Switzerland) lists several adverse health effects known for aviation noise, among them cardiovascular disease, sleep disturbance, annoyance and cognitive impairment with good evidence of a strong relation between aircraft noise and annoyance (other researchers speak of 'substantial evidence' [25] (p. 43) when qualifying the association of noise exposure with annoyance). Based on international studies comprising over 17,000 subjects, the WHO strongly recommends that aviation noise levels do not exceed 45 dB Lden during the daytime and 40 dB Lnight during the night, in order to mitigate any adverse health effects [26].

Noise annoyance can be understood as a complex psychological phenomenon [27] comprising at least three elements [28]:

- (1) The experience of repeated noise-related disturbance and the behavioral response to cope with it.
- (2) The emotional/attitudinal response to the sound and its disturbing impact.
- (3) The perceived lack of capacity to cope with the noise [29]. The coping style can either be problem-oriented or emotion-oriented, where problem-oriented coping is more proactive and the latter more reactive in nature.

In the context of airport noise, it has been shown that perceived control can be a more powerful predictor of several outcomes than noise exposure itself, and that the perception of noise as uncontrollable is linked to several negative effects [30].

Communities can differ in their tolerance to noise. The community noise tolerance level (CTL) is described as the noise level at which half of the population reports being "highly annoyed" and is measured using a standard set of questions. In addition to personal, situational, and cultural influences, the rate of abrupt change in noise levels in recent years has been identified as a factor that influences the community noise tolerance level, with airports that have a high rate of change leading to higher annoyance levels than airports with a low rate of change [31].

Research has also found that the same objective noise level measured in dB can lead to different CTLs at different locations [32]. Furthermore, at the same total noise level, a longer relative duration of quiet periods reduces noise annoyance significantly [33].

Physical measures of sound exposition are said to explain about one third of the variance of individual annoyance reactions [34] (p. 45). Accordingly, not only noise reduction at the source or by physical protection measures can mitigate noise, but also non-acoustic strategies: "the observed influence of several non-acoustic factors such as fear, perceived control, and trust in authorities suggests that communication strategies addressing these issues could strongly contribute to the reduction of annoyance, alongside or even in the absence of a noise reduction" [25] (p. 43).

Most of the findings on aviation noise relate to classic air traffic, jet aircraft, and helicopters, so they have to be downscaled when applied to UAM. The industry seems confident in the potential of

producing low-noise vehicles [9]. According to [35], several design approaches are supposed to have a potential of reducing noise at source for electrical vertical takeoff and landing vehicles (eVTOL) by between 3–5 dB, (reduced tip speed, swept blades, increased blade count) or about 1–2 dB (reduced blade loading). The most promising improvement, however, is seen in optimizing the approach path, with a potential of 5–10 dB noise reduction.

However, with UAM also new noise issues have to be considered, as there might be acoustical interferences of multi-rotor configurations [36], certain aspects of tonality typical for drones, e.g., quadcopters [37], special influences of ambient weather conditions on sound levels and quality [38], or the implications of different flight paths for human perception [39]. In addition, quadcopters, for example, are controlled by varying the speed of every rotor individually, inducing pitch and yaw of the vehicle and changing the sound constantly, leading to more content at higher frequencies compared to conventional aircraft [40]. Discussing some immanent characteristics of UAM vehicle noise, it is stated in a report for ICAO: “There is preliminary evidence that the public may be concerned with these new noise sources intended for transportation and package delivery” [34] (p. 57).

With 24/7 operation envisaged, with airspeeds predicted to exceed 100 mph, and with the basic physical fact that when air meets a structure it produces sound (true for propellers as well as for the cabin), the noise problem will be persistent with all types of UAM. Not only that, but UAM noise will be an additional factor along with other environmental noise sources such as road, rail, traditional aviation, and industry: it will “come on top” for all the citizens living or working on higher floors in the tall buildings of today’s urban canyons.

4.2. Noise Measurement

In the context of monitoring environmental indicators, noise measurement has made remarkable progress. Beginning with isolated measurement units in fixed locations, for instance on noisy streets or below the glide path of an airport, nowadays information and communication technology is used in wireless networks to provide real-time measurements from acoustic noise sensors [41]. This technology is used at airports worldwide and involves community engagement with the help of web-based tools displaying flight tracks, altitudes, and noise levels registered at the noise-monitoring stations. In [14], a case study for the use of such system in community engagement is provided. In it, they recommend providing real-time measurements to residents in order to achieve transparency in the communication.

For UAM, comparable community services should be available from the beginning. The noise data should stem from real-time measurements. Combining UAM traffic data with incoming noise measurement files using timestamps and/or geopositioning data will allow UAM noise to be distinguished from other environmental noise sources when necessary. The data should be stored geographically on regional maps. Track colors represent noise intensity at ground level, with track density showing the frequency of flights at a given location. Noise profiles should be generated and analyzed under public control and be accessible to the public. “Providing open-source data that can inform new technological developments, while keeping communities of stakeholders engaged, helps promote domestic technology growth and enables innovation . . . ” [42] (p. 9).

Wireless acoustic sensor networks initially relied on a limited number of high-accuracy commercial measurement devices. However, the recent development of low-cost acoustic sensors and signal processing techniques based on big data has opened the discussion about using crowd-sourced data collection for the environmental monitoring of several pollutants in urban areas [43], with noise being a prominent example [44]. With the increasing availability of sensors, which are affordable in large numbers and integrated into almost every current smartphone, mobile crowd sensing networks can become a common service in smart cities to support municipal agencies in urban planning and regulation. According to [43], two different measurement modalities will be available to the user: opportunistic and participatory sensing. While the opportunistic measurement uses the microphone continuously and automatically sends data, the participatory measurement is user defined and allows subjective evaluation data to be added, such as a description of the scene and situation, ratings of

sound tonality and loudness, perception of flight pattern dynamics, personal mood, and last but not least, actual noise annoyance.

5. Participatory Noise Sensing

The technical challenges for engaging smartphones in noise measurements have been assessed several times, starting as early as 2010 [45]. In recent years, there have been large advances in noise mapping using smartphones. In [46], the requirements for noise measurement as laid down in the European Noise Directive are listed, and the study describes their meaning for mobile measurements using a certain type of smartphone. Applications available today enable residents to submit noise data and provide additional information directly from their smartphone [45]. When proposing a concept of citizen PNS, [47] list more than ten different smartphone tools for noise mapping. An in-depth description of an open-science crowdsourcing application for producing community noise maps is provided by [48].

Importantly, in order to reach more than 75% of potential users, a tool for participatory noise sensing needs to be available on both of the major smartphone operating systems. The practical implications of developing an application for sampling experiences related to aviation noise are described by [49], including aspects of data protection and privacy.

Using individual smartphones for sensing might bring about calibration issues, but every new generation of devices typically outperforms their predecessors; as according to [50], there is a significant relationship between phone age and its ability to measure noise accurately. However, in a recent feasibility study of smartphone applications for noise measurement, there was only one current Android application recommended based on its calibration features [51]. The same study compared sound recordings with different types of smartphones in different technical layouts. The final recommendation was to use an external collar clip microphone with a calibrated smartphone of the current generation.

By using smartphones for noise mapping, citizens are able to actively engage and contribute real-time measurements [45] that closely represent the individual's actual noise exposure. In addition, residents can contribute to noise mapping with personal data while still maintaining user anonymity. Furthermore, PNS enables learning among users. When using an application collecting both objective and subjective data, [52] showed that as experience increases, estimations more accurately reflect the result of objective measurements, and the amount of additional subjective information provided increases. Overall, exposure to information from the noise application led experienced users to have a more precise evaluation of their environment than novices did. Furthermore, [43] consider providing feedback to the user, for instance on mean values of ratings, as a way of enabling social adjustment and encourage engagement. User meetings or "noise mapping parties" as mentioned by [47] (p. 153) will contribute social aspects of learning.

The processing of noise sensing data is complex and depends on the general layout of the tool in use. For 'noise capture', for instance, the three different files are transferred to a remote server and processed in a spatial database as described by [48]. A different setup using a cloud solution is described by [53] as being very energy efficient; here, groups of users can be formed using only the leader's smartphone for data transmission, thus saving power consumption. Challenges of data management data modelling and smartphone energy consumption are discussed in [43].

However, the most important question relates to the validity of noise sensing data: can we trust the sound recordings to truly represent real world conditions?

This has been shown, among others, by [46] comparing sound levels in maps resulting from PNS with those simulated on statistical data from earlier years, finding high similarity concerning sound level distribution. Furthermore, in the context of establishing city noise maps [54] compared results of smartphone noise sensing and sound level meter for two different locations finding noise maps could be accurately build from applications running on calibrated smartphones. The precision of the noise mapping becomes higher with the number of samples, finally also allowing the calibration of noise maps created on calculations and simulations with real-time measurements. Comparing smartphone

applications with sound level meters in the laboratory and in different field locations, [55] found strong agreement for audible frequencies between smartphone sensing and sound level meters in the laboratory as well as in the field, whether representing noise from heavily trafficked roads, oil and gas construction sites, or airport operations. Using inexpensive external microphones further increases the reliability of measurements and makes smartphone applications “reasonable and cost-effective proxies of reference measurement devices to explore noise pollution” [55] (p. 556).

Using a set of 24 different current phone models, [56] validated a certain smartphone calibration process. This worked well for all those models allowing access to unprocessed audio; however, as no external microphones were used, results showed an influence of the different cover or cases used for the phones. Subjects participating in the trials could successfully calibrate their phones and determine the environmental noise of a housing estate and a natural park at different times in terms of sound pressure level and frequency spectrum.

Finally, the importance of a meaningful introduction of volunteering subjects to the task also contributes to PNS validity; when studying errors in non-expert smartphone-based sensing, [57] found data quality and thus PNS validity to be enhanced best by providing technical measures (e.g., status indicators) and instructions (a short tutorial), and that only the combination of both kept perceived usability as well as user experience high.

Compared to other methods of data collection, PNS data are superior, since they are the closest representation of the true noise perceived by the citizen and can offer additional subjective information. Artificially calculated measures are likely to underestimate the true noise values, as they can never include all data relevant on site. However, measurement data from unsupervised stations or data harvested by volunteers need to undergo sound-spectrum analysis in order to check for outliers and accuracy before being included in the database.

6. Noise-Optimized UAM

To optimize UAM regarding noise emissions, an urban air traffic management (UATM) system at the city level needs to track all flights in urban airspace. Noise profiles should be generated ad hoc and analyzed under public control. The data should be stored geographically on regional maps, with track colors representing noise intensity at ground level, and track density showing the frequency of flights at a given location. This map should be accessible to the public and constantly be updated, and provide the ongoing basis for calculating noise impact.

Whenever possible, the UATM system should be able to adjust requested flight patterns in real-time so that the noise-burden is shared among residents in an objective and transparent manner. For instance, within a dynamic skylane network, altitudes could be adjusted, or the lateral flight route could be adapted, based on the prior noise load at a given location [58]. Preferably, no fixed flight corridors would exist, in order to allow for the flexible use of urban airspace, thus providing the optimal distribution of noise burden among residents.

7. Conclusions

Air mobility will come to our cities within the next decades. It will come as an additional platform in urban mobility and will be an additional source of environmental noise for citizens. It will receive extra public attention because it will be used by a relatively small segment of the population, but it will produce elevated noise volumes for many.

One way to support the successful introduction of UAM is to invite residents to actively participate in noise sensing by using smartphone applications. In doing so, the major elements of noise annoyance can be positively influenced:

- Using the application will increase the capacity to cope with noise in a problem-oriented, and thus proactive, way.
- The emotional/attitudinal response to the sound and its disturbing impact will thus be moderated.

- The experience of repeated noise-related disturbance will be limited due to the adjustment of traffic patterns.

This kind of application should be available proactively for all platforms from the onset of air taxi services at no cost for the user. It could be even more successful if additional smart city functions were offered, such as linking with public services, other transportation systems, or an option to request a temporary flight ban over a certain location, e.g., when there is a neighborhood festival.

By referencing individual noise loads, as proposed in this concept, the onset of UAM would be supported while simultaneously safeguarding the wellbeing of citizens. The less noisy urban air taxi operations are for the residents, the more successful and sustainable its introduction will be.

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