Managing UAS Noise Footprint

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Abstract

This paper identifies urban air mobility (UAM)[1] noise challenges and analyzes potential solutions for managing noise to ensure sustainable growth. We review existing scientific literature on unmanned aerial vehicle (UAS) noise impacts, including relevant literature on manned aviation noise impacts and define technical terms. We identify gaps in research and knowledge on UAS noise generation, mitigation and effects. To accommodate high-density UAS operations, we propose a balanced approach that encompasses many solutions and identifies potential trade-offs for flights over noise-sensitive areas. To manage urban air mobility noise, we recognize public perception challenges and discuss annoyance levels. Finally, we evaluate governing rules and highlight the importance of working with all stakeholders in defining standards for UAM.

1. Introduction

There are many benefits of implementing urban air mobility in our daily lives, from reducing our commute times to package delivery; surveying traffic or wildlife; as well as providing emergency assistance. Nevertheless, much like aircraft and road noise, UAS operations may negatively impact communities by reducing their quality of life. Annoyance to noise is a complicated subject that has been studied for decades and is a focus of many research efforts today [1]. Noise is defined as "unwanted sound" and is considered one of the most detrimental effects of aviation [2]. To overcome this, we need to consider strategies that build community tolerance before implementing large numbers of UASes in the community's backyard.

If not managed properly, adverse community response can result in social and political pressures. Overly prescriptive regulatory responses to those concerns may impact UAS operators by limiting their ability to expand operations. Civil aviation authorities have vested responsibility of regulating civil aviation, including Unmanned Aerial Systems (UAS). In the context of aviation noise, there are similarities and differences, and important lessons/best practices that do carry over to UAS operations.

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[1] Urban Air Mobility (UAM) as defined by NASA, is a safe and efficient system for air passenger and cargo transportation within an urban area, inclusive of small package delivery and other urban Unmanned Aerial Systems (UAS) services, which supports a mix of onboard/ground-piloted and increasingly autonomous operations.

Current research on UAS operations focuses on performance, capacity, and safety. Notably, only a small body of research focuses on noise impacts. When discussed, it is often limited to acoustical annoyance and current legislation. Accounting for noise in conceptual designs is difficult due to the complex relationships between design variables and potential issues that arise with large scale-systems. Inherent uncertainties exist due to UAS performance, size, and noise prediction methods. Nevertheless, omitting comprehensive noise studies from the assessment process means denying that the noise concerns exist. To accommodate high-density UAS, a fundamentally different approach to mitigation is needed. Thus, we introduce more comprehensive solutions to managing urban air noise.

2. Evolution of transportation noise

Railroads shaped the 19th century and highways together with aircraft shaped the 20th century. Noise pollution has been a by-product of each of these transportation modes. The 21st century has the potential to be shaped by UAS operations significantly because of the proximity of operations, variety of vehicles, and the planned airspace utilization [3]. Limiting the amount of noise these vehicles generate and overcoming noise annoyance of communities will be vital to the successful widespread expansion of UAS operations.

Aviation noise has been studied extensively, and we can leverage this knowledge by incorporating lessons learned and best practices. It is equally important to identify forward-looking and proactive methods. Another key fact to remember is that highways were built in the 1950s, and the last major airport built in the US was in 1995 [4]. Major arrival and departure routes were established over 40 years ago and have remained mostly unchanged. Historically, airports were built outside of urban areas, but with time and as the population grew, many communities expanded to within the vicinity of airports. People bought houses aware of aircraft noise but were willing to accept it due to lower living costs. People exposed to UAS noise are likely not going to have this option since UAS operations will be entirely new after years of living in a setting without their presence.

2.1. Sustainable Growth

As UAS operations increase over residential areas, it is likely that we will expose more people to aviation noise. While conventional aircraft are much louder, they also fly much higher than UASes. With the planned proximity and frequency of UAS operations, the noise exposure is no longer limited to the vicinity of airports or the existing road infrastructure.

POPULATION EXPOSED TO SIGNIFICANT AIRCRAFT NOISE VS. AIR TRAFFIC (US) [1], [30]

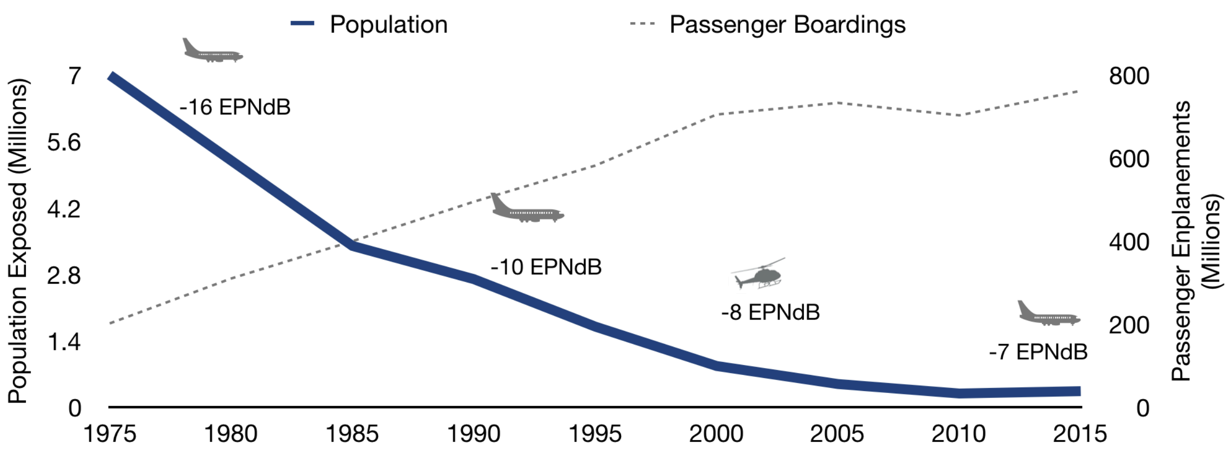

Figure 1. With stringent aircraft noise certification standards (effective perceived noise level (EPNdB) decrease) the population exposed to significant aircraft noise has decreased as the number of passenger boardings in the U.S. has steadily increased since 1975.[1], [30]

In general, the global population exposed to significant noise levels is expected to grow due to the increase in manned commercial air traffic [5]. For this reason, noise exposure has to be consistently reduced through continued innovation of quieter technologies, implementation of optimized procedures that reduce noise, and other noise abatement initiatives. The same holds true for the UAS community. The platforms that will manage high-volume and autonomous UAS operations must be flexible and scalable enough to accommodate growth while being able to apply evolving noise reduction policies.

Over the last 40 years, there have been steady improvements in aircraft noise reduction, as evident in Figure 1. The population exposed to significant noise levels was reduced by approximately 90 percent between 1975 and 2000 [1]. The latest aircraft certification standards require that aircraft built today are 25dB (75% noise reduction) quieter than aircraft in the 1970s [6]. Although regulations and policies often tend to be behind the curve, it is evident that there has been positive progress.

However, the implementation of widespread UAS operations is likely to be measured in years and not decades. Airports and roads need substantial investments and have significant infrastructure constraints, whereas UAS operations can be rolled out much faster and at a lower cost due to the light infrastructure requirements. Under these circumstances and with favorable policies that allow operators fast implementation and unrestricted growth, noise disturbances can rapidly become a concern.

2.2. Managing Aircraft Noise is Evolutionary

The arc of community concern and regulatory response over new noise impacts follows several common steps. First, noise issues typically start with the operator's or regulatory agency's lack of knowledge or denial of the problem, which causes further community annoyance. This contributes to the lack of trust between operators, regulators, and communities. Second, in an attempt to minimize noise impacts, officials attempt to measure the effects of annoyance by conducting comprehensive noise survey studies. Third, as a result of these tests, specific policies on noise abatement procedures and operational restrictions are implemented. This is usually a several-years-long process which communities perceive as taking too long. Lack of quantifiable goals in reducing noise and initiatives with no deadlines create uncertainty among communities. Under these circumstances, building trust and credibility to increase community tolerance becomes challenging. The strategy of managing noise is reactive rather than proactive. Finally, active community engagement and collaboration, which is a superior business approach that moves beyond the legislative requirements, typically comes last. Today's technology and data-driven decision making can help us predict some of the unfavorable situations and should be leveraged wherever possible to gain understanding and drive favorable implementation policies [2].

3. UAS Noise Impact

3.1. Holistic Approach

Noise impact assessments affect the regulatory process. A holistic approach when assessing noise needs to consider acoustic, environmental and personal annoyance factors [7],[8]. The following are findings of aviation noise impact that may hold true for UAS operations and should be considered when defining what constitutes a noise impact.

- Repeated noise events, regardless of measured sound levels, present an opportunity for annoyance [42].
- The longer the noise exposure duration, the greater the potential for annoyance [43].
- Spectral characteristics affect the perception of noise. Specific tonal ranges are generally more annoying than broadband noise.
- We react differently to sound levels depending on our relationship to regulators and operators. If we hold a favorable view toward UASes, we are likely to be less annoyed by the noise.
- Acoustic properties of sounds are different depending upon weather and topography.

- Most noise disturbance reports received by airports are from communities outside the significant noise exposure area [27].
- An increase of 5-6 dB in noise exposure is clearly noticeable and can result in high annoyance levels [10].
- Summer months can expose you to more noise by having open windows.
- Background noise at night is lower than during the day.

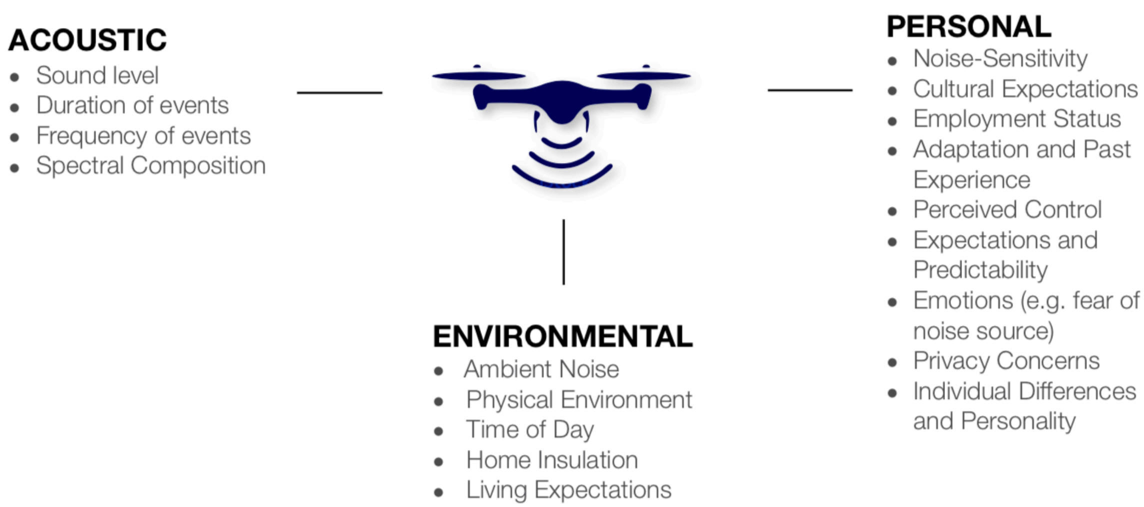

Figure 2. Noise impact is driven by a range of disparate factors, many of which are subjective to the individual and therefore difficult to quantify.

4. Quantifying sound

To minimize the impacts of aircraft noise, regulators have implemented noise standards based on quantifiable modeling. Before we discuss some of these standards, we review the state of research in UAS noise level measurements. It is important to note that findings on the characteristics of UAS sounds are based on small-scale analysis and vary among studies. Therefore, there is some doubt as to the accuracy of certain conclusions. Due to the lack of comprehensive large-scale studies, there are many general assumptions and estimations. The most important takeaway from reviewing the existing literature is that we need to conduct more studies and share data to support such assumptions.

4.1. About UAS Sound

UAS rotor blades emit a sound that is currently impossible to eliminate. To produce lift, you have to move air, and a by-product of that is noise. We can make UAS vehicles quieter but not silent. The primary sources of noise from UAS vehicles are the rotors, followed by the electric motors [11], [12], [13].

To describe sound vibration frequency or “pitch" of UASes we use Hertz (Hz) as a unit of measurement. For example, the sound harmonics generated from a typical quadcopter are heard in the human mid-frequency range, around 6 kHz, and dominated by high and sustained tones at the blade passing frequency (BPF) [14]. Multicopter BPFs tend to be uniform in hover stage but become separated in forward motion as rotors are driven at different speeds to maintain forward flight [40]. Moreover, compared to 1 or 2-rotor operation, the 4-rotor interaction produces a significant non-linear increase in broadband noise and thus points to the sound created due to multi-rotor interaction [14]. In either case, acoustic energy spectrograms show that the rotor noise dominates the small UAS noise signature due to unstable pressure fluctuations (turbulence), blade vortex interaction, rotor speed variations and unsteady force noise that occurs periodically from the disturbed inflow due to UAS design. These factors make it challenging to reduce the noise of a UAS and predict community annoyance [40].

We measure sound level with decibels (dBA) from the threshold of human hearing, 0 dB, upward towards the threshold of pain, about 120-140 dB. [2] Typically, a change of 3dB is barely noticeable, and a difference of 6dB is clearly recognized. Small UAS noise levels range from 60 to 70 dbA at distances of less than 50 meters [15]. According to ICAO, small UAS (sUAS) are expected to be on average 6 to 9 dB quieter than existing small single-engine airplanes [33].

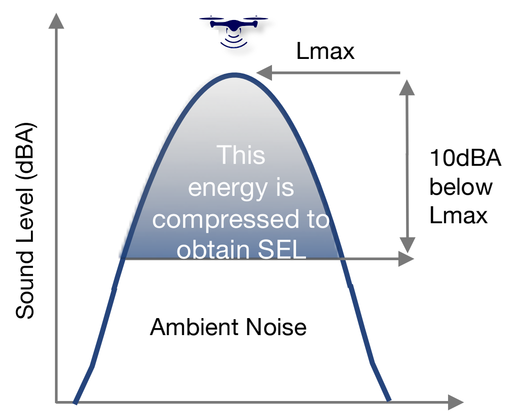

Figure 3. Sound Exposure Level (SEL) is calculated as the integral of a given sound event above the ambient noise level.

4.2. Short-Term Annoyance

To describe short-term annoyance, or in other words a single aircraft noise event, we use Sound Exposure Level (SEL), measured in dBA. [3] For a maximum decibel level of an aircraft event, we use Lmax. [4] For

[2] dBA stands for A-weighted decibel. Decibel unit measures the loudness of a sound and is computed as the signal to noise ratio. A-weighting is used to adjust for frequency range of human hearing (between 20 Hz and 200 kHz). An increase of ten decibels is perceived by human ear as a doubling of noise. Because decibels are computed logarithmically, to double the amount of noise, you need ten times the sound energy.
[3] Sound Exposure Level (SEL) of a noise event is measured over time between the initial and final points when the noise level exceeds a predetermined threshold and its energy is compressed into one second.
[4] The maximum noise level (Lmax) is a measurement of the peak level of a noise event.

instance, at 15 m altitude flyover, Lmax of a DJI Phantom 2 quadcopter was measured at 63 dBA, and 68 dBA for the Prioria hexacopter [40]. An additional measure, used during the aircraft certification process, is Effective Perceived Noise Level (EPNL), measured in dB. EPNL describes the relative loudness of an individual aircraft operation based on frequency spectra and duration of the sound. Both SEL and EPNL are used to measure the noise exposure of a single aircraft noise event. EPNL values are numerically higher than SEL; however, there is no direct relationship between the two metrics. EPNL is based on the Perceived Noise Level (PNL) and not on the A-weighted sound level. Because of this, we cannot measure EPNL directly and need to apply additional calculations that take into account perceived human annoyance [15].

Various studies have gathered measurements of SEL from small UAS flyovers in relation to the observer's height (Figure 4). Given these levels, many vehicles are in the perceptible "loud" range at relatively low altitudes. This shows the need to introduce noise reduction strategies in the vehicle as well as the need to be routed away from noise-sensitive areas since vehicle sound levels will most likely be bothersome to underlying residents. This is a small data sample, but it is enough to show that we can't assume that UASes will be able to fly freely and that people will embrace them. Further research would help answer questions about lateral and vertical noise propagation, and whether flying at higher altitudes would be less bothersome to observers on the ground, even if the noise footprint covered a larger area. When compared to aircraft or helicopters, UASes are significantly quieter, but this is all relative to the proximity of operations. By doubling the distance, noise typically reduces by 6 dB. UASes are expected to

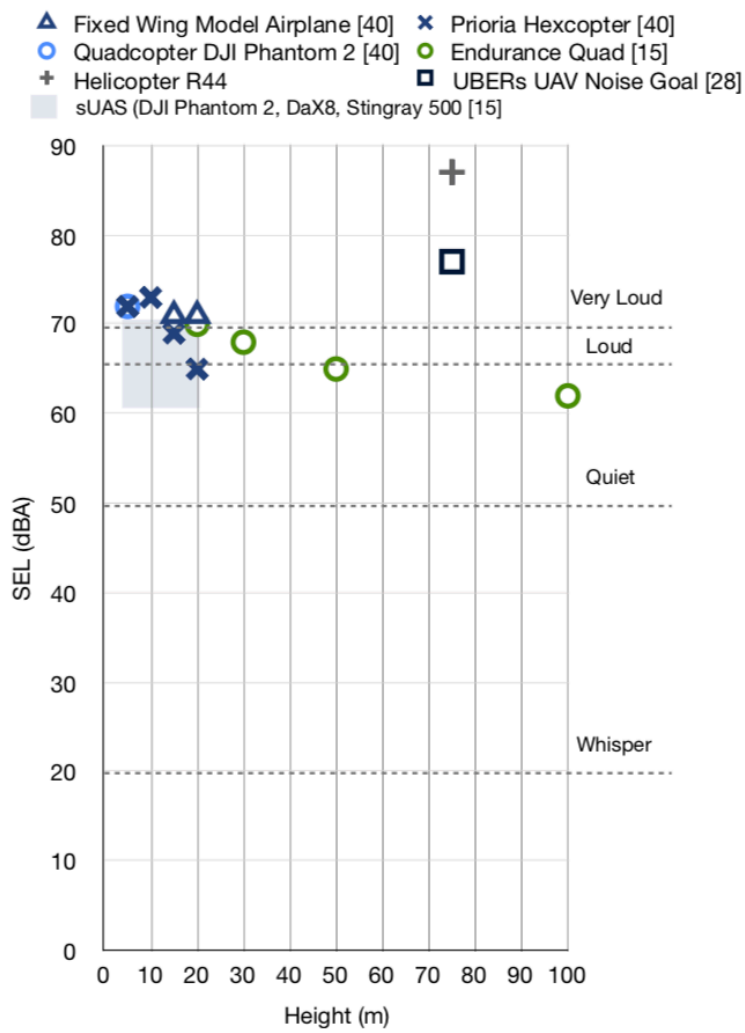

Figure 4. Comparison of SEL values for a variety of UAV models by operating altitude.

operate at lower altitudes than conventional aircraft, and they can appear to be just as loud as other air traffic flying higher.

4.3. Long-Term Annoyance

To describe the long-term noise impact, we use Day-Night Levels (DNL)[5]. Single event noise levels specified in the previous section and ambient noise levels make up hourly LAEq[6] that is then used to calculate DNL. Therefore, DNL is a representation of noise levels over a day with added dB penalties to account for the higher sensitivity to noise at night (10 pm to 7 am) and the expected nighttime decrease of background noise levels. For example, each nighttime event is measured as if ten daytime events had occurred. This metric takes into account the noise intensity, time of events, frequency of operations and duration of exposure [16]. It is a uniform way of considering the impacts at various concentrated zones of noise. Airport significant noise exposure areas are modeled based on a cumulative exposure to sound over a 24-hour period (daily DNLs), averaged over a year on the basis of annual operations. Areas near future vertiports or distribution points for package delivery UASes could use a similar quantifiable methodology to assess their noise impact.

In the United States, the FAA considers 65 DNL as a threshold of significant noise exposure while most other countries use 55 DNL. The DNL metric has been useful in the past as an

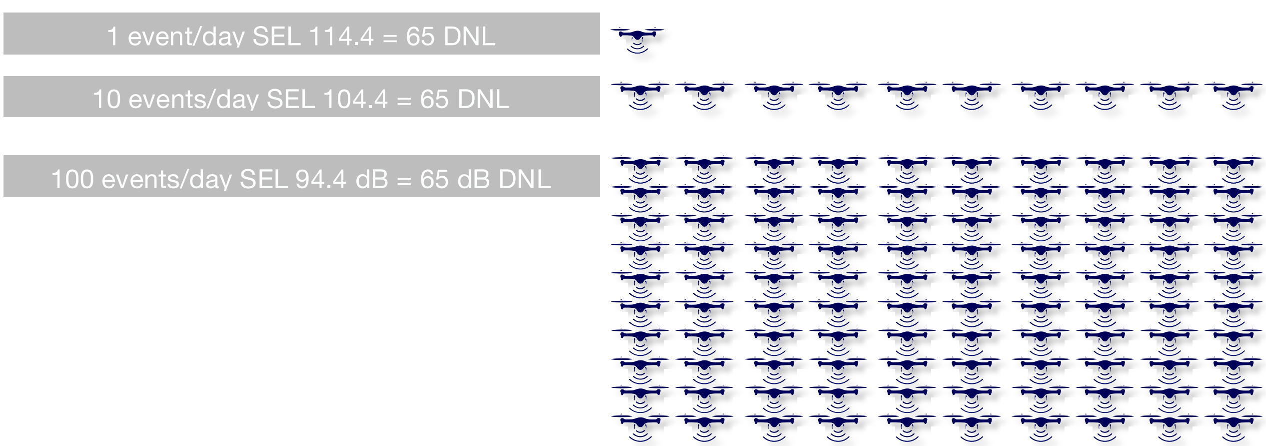

Figure 5. Because the DNL measure aggregates a day's worth of noise events, the same DNL value may represent a broad range of operational scenarios that an observer on the ground would experience as being very different from one another.

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5 DNL- This metric is used to assess and regulate aircraft noise exposure in communities surrounding the airport. Established acceptable level of aircraft noise in US is 65 dBA DNL.

6 Equivalent Continuous Level (LAeq) is the total sound energy measure over a defined period of time.

“economic metric” for airport noise exposure maps, which provide the means for funding of home noise insulations programs and a basis for zoning rules. In spite of that, DNL is widely considered among communities as an outdated and incorrect representation of community noise disturbance. To understand why, consider that in Figure 5, all three scenarios show equivalent 65 DNL environments [16].

A community can experience one extremely loud event or hundreds of small noise-dose events and be considered the same. The FAA’s policy direction is that if you are within the 65 DNL you are significantly impacted, and if you are outside of that (e.g. 64 DNL) you are not affected.

For the above reasons, it is unrealistic to expect that the current quantitative metrics used by FAA may enable high-density UAS operations [15].

In contrast to FAA policy, 55 DNL has been established by the Environmental Protection Agency (EPA) as the threshold of acoustic impact and is believed to be the “new 65 DNL threshold” due to recent studies which show higher annoyance than when thresholds were initially established in the 1970s. It is therefore beneficial for operators to work with regulators and other stakeholders in quantifying UAS noise standards. It is essential to research and adopt new metrics that will allow UAS growth with community-wide support.

4.4. Integrating UAS Operations over Communities

The noise level scale in Figure 6 shows the average DNL noise levels for various types of settings. Remember that noise is a logarithmic value, and an increase of 10 dB is perceived as doubling of loudness. Examples in Figure 6 are the average SEL noise values. This gives us an idea of where small UAS vehicles such as package delivery drones typically weighing less than 55 pounds fit into the community noise levels. For the foreseeable future, UASes are going to be louder than ambient noise in most cases and coupled with repeated events have the potential for noise disturbance to communities [12].

4.5. Noise Modeling

Current scientific research on UASes has been primarily focused on actual noise level measurements of individual UASes. While this is important, noise modeling is needed to extrapolate results to a large geographical area and predict the effects of noise from high-density operations. Modeling can be used to provide historical background, predict noise levels, and

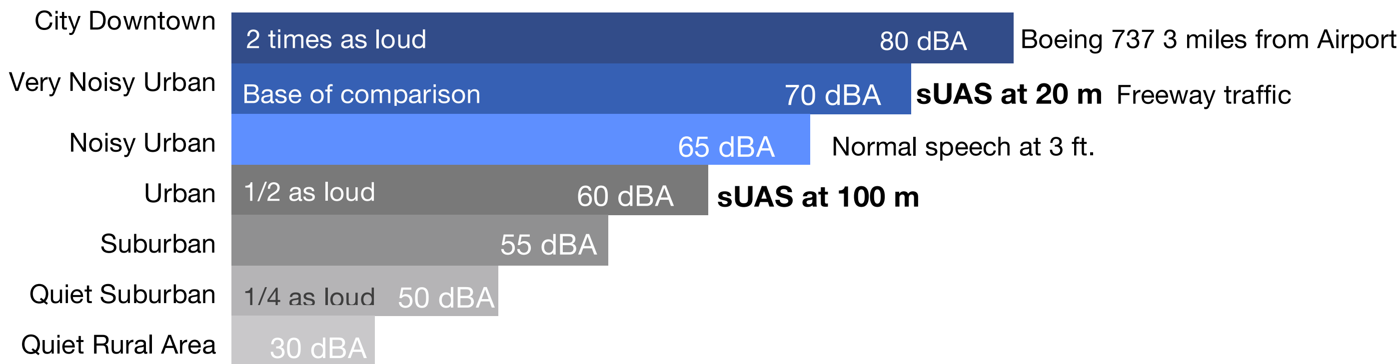

Figure 6. Average DNL and ambient noise levels in various settings.

track trends. For example, FAA has been using AEDT[7] to dynamically model aircraft performance in space and time to compute aircraft noise [17]. The output of AEDT are noise contours showing the extent of noise exposure. The National Transportation Noise Map [18] is another example of noise mapping and can be a valuable visual explanation of the noise exposure to underlying communities. Airports and freeways are concentrated zones of noise, whereas UAS traffic is likely to be more dispersed. Therefore, new noise models have to be researched.

[7] Aviation Environmental Design Tool (AEDT) is a software system that models aircraft performance in space and time to estimate fuel consumption, emissions, noise, and air quality consequences. AEDT is a comprehensive tool that provides information to FAA stakeholders on each of these specific environmental impacts.

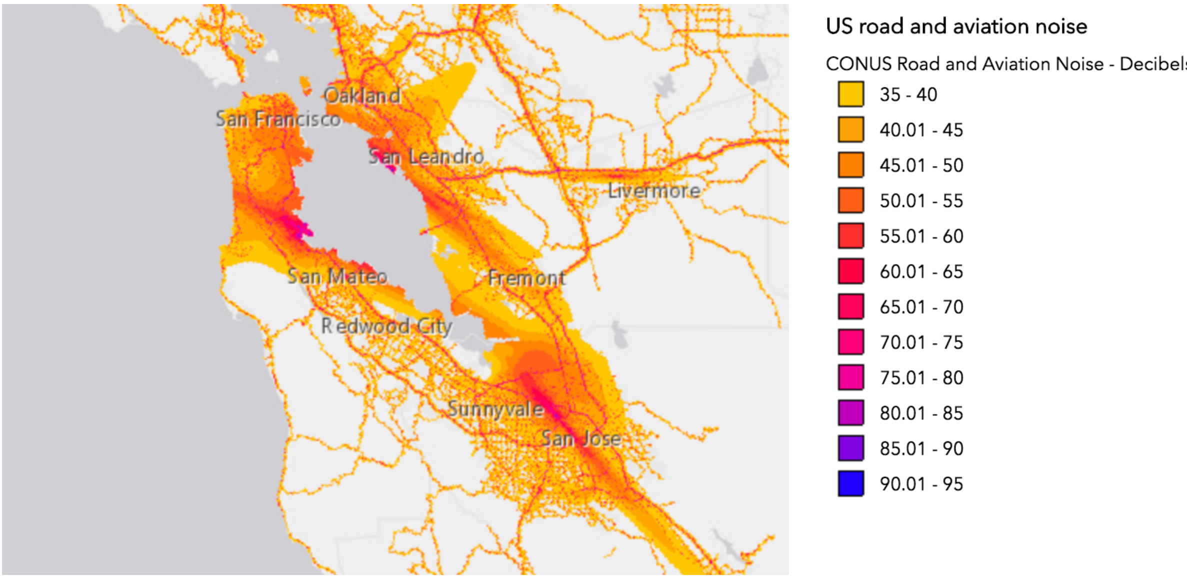

Figure 7. The San Francisco Bay Area, as depicted on the National Transportation Noise Map [18].

One such example is a fairly basic model used by Berkeley researchers to estimate the ambient noise levels generated by small UAS based on population density of the region and create a noise footprint. Research showed that noise levels alone would not be a nuisance; however, the proximity of operations can lead to substantial annoyance. Further, when the UAS traffic density and reference noise level changes, the noise pollution metrics change linearly. This means we could effectively scale UAS operations without significantly increasing noise. Based on the UTM capacity estimation research, safety seems to be a much larger capacity-limiting factor than noise. [19]

While sound measurements and noise modeling accurately describe the acoustical impact, they fail to capture the personal and environmental effects of annoyance. Because not all annoyance is acoustically quantifiable, we can use flight track density and heat maps to evaluate other variables for a balanced strategy of mitigating noise.

5. Community Perception

5.1. Understanding Annoyance

A NASA investigation into the psychoacoustic properties of small UAS suggested that there may be a systematic difference between the annoyance response generated by the noise of the UAS and vehicles on the road. When the UAS and car sounds were played to subjects at the same volume, subjects found UAS noise more annoying. This presents a significant risk to UAS operators that expect no community opposition as long as the sound of their UAS is no louder than conventional truck package delivery [15]. This conclusion makes sense when considering the annoyance levels of aircraft noise and road noise as depicted in Figure 8.

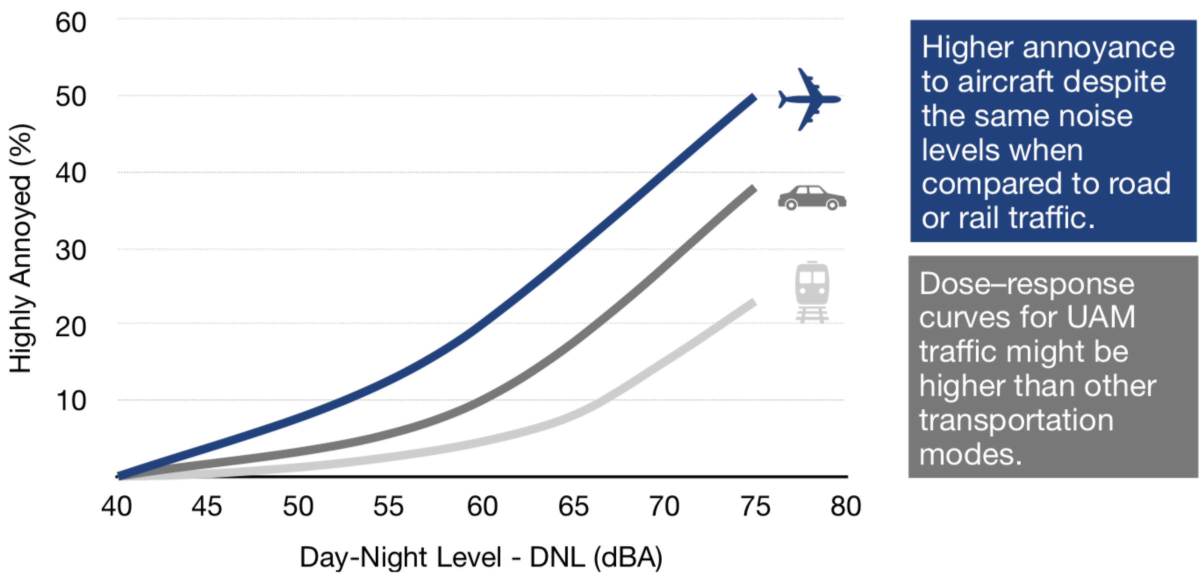

Figure 8. Schultz dose-response curves correlating DNL to community annoyance for several transportation modes.

Figure 8 presents a relationship between social response and noise levels. Current noise thresholds used by FAA are based on the resulting dose-response curves that were developed in the 1970s, also known as the “Schultz Curve” [20]. Recent aircraft noise studies show higher importance of non-acoustical annoyance factors and speculate that the dose-response curves lay higher [21],[22]. Airports noted this primarily with the higher number of noise reporters and the number of reports they submit. Although local community reactions vary significantly based on their relationship with regulators and operators, the dose-response curves are a uniform way of describing annoyance and applying it to any given community. Future research needs to develop noise-dose response curves for UASes flights to gain a better understanding of the extent of the problem. At this time, we can only speculate that the dose-response curves for UASes are going to be higher than any other transportation mode.

6. Noise Mitigation

6.1. Balanced Approach

The most gain in mitigating aircraft noise has been achieved through new, quieter engine and aircraft design technologies and regulated phase-outs of older aircraft. However, this is not a single approach to mitigation. Principal elements of the balanced approach to managing aircraft noise can also be applied to UAS operations.

Guidance on the balanced approach was issued by ICAO and adopted globally by most civil aviation authorities. While reduction of noise at source applies to all members, land use planning and noise abatement procedures remain within the jurisdiction of the member state. Once the above options have been exhausted, certain operating restrictions can be established by member states. The extent of those efforts varies: several elements are not implemented by the FAA, as they inherently contradict US regulation [24]. Elements were put in place for aircraft noise to achieve maximum environmental benefit most cost-effectively [23]. In the second edition, ICAO recognized the importance of another element, community engagement.

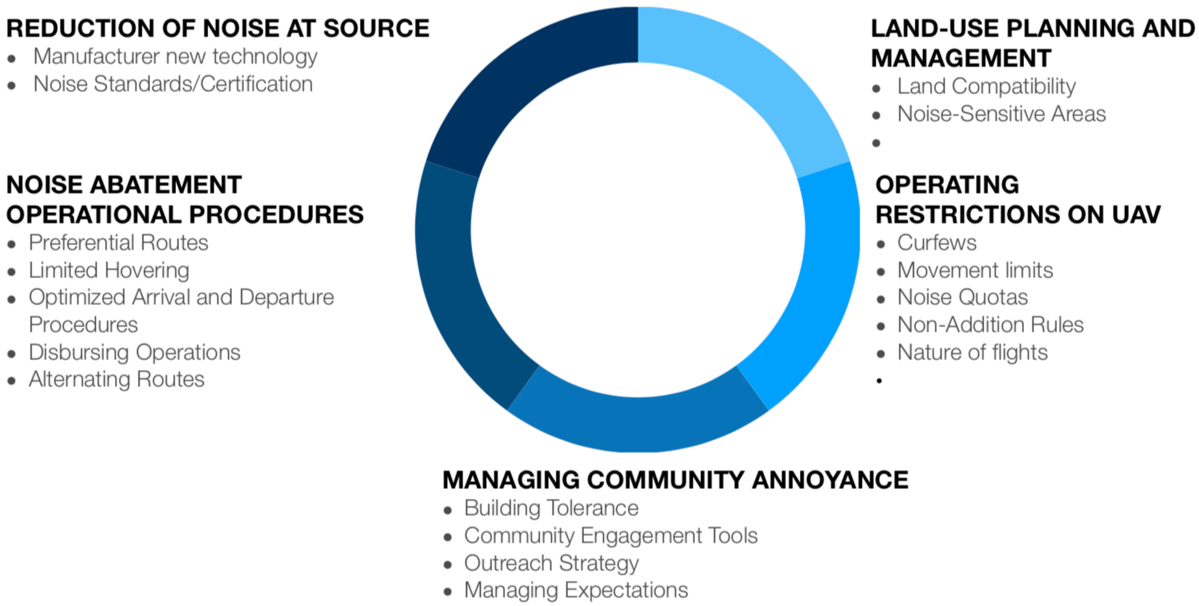

Figure 9. A balanced approach to noise mitigation includes a combination of new procedures, outreach, operating limits and planning.

6.2. Reduction of Noise at Source

UAS Manufacturers: Reduction of noise at the source can be one of the most effective ways of mitigating UAS noise. So far, efforts have been aimed at avoiding UAS detection in military usage; improving UAS cinematography equipment; and decreasing disturbances during wildlife conservation surveys. UASes are getting quieter in some cases by 6 decibels, mostly due to passive noise cancellation [25]. Other advances can potentially be gained through design changes, mainly by reducing rotor tip speeds on multi-rotor and hovering vehicles [26].

Noise standards/certification: ICAO indicates that new noise standards might be necessary as new vehicles come into use [33]. Likewise, assuming similar airframes and propulsion systems are used, noise requirements for current aircraft categories will apply to UAS [33]. The degree of noise regulation in the certification process is likely to vary based on the UAS category. To ensure achievable noise reduction goals this work has to be coordinated with the manufacturers.

6.3. Operational limitations

A variety of strategies currently used to mitigate aircraft noise could be applied to UAS operations as well. However, each one introduces possible tradeoffs in route efficiency, airspace capacity limits and practical enforcement mechanisms.

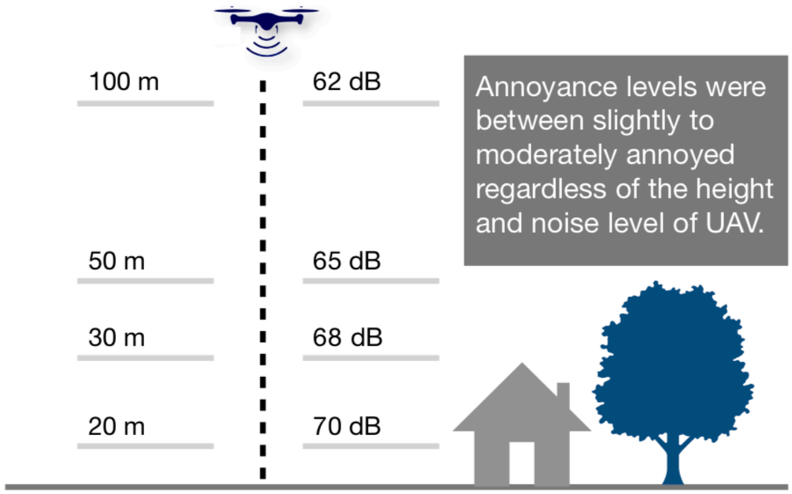

Figure 10. NASA research found that increasing operating height above ground might not always effectively alleviate noise impact. Even though there was an 8 dB difference in measured SEL, annoyance levels remained firmly between slightly and moderately annoyed [15].

Preferential Routes: This is one means of re-directing UASes away from noise-sensitive areas. When operationally feasible, preferential routes can have specified headings, altitudes, and be in effect during certain times of the day or at all times. Use of such routes can significantly reduce the noise footprint.

Optimized Arrival and Departure Procedures: Similar to preferred routes, optimized arrival and departure procedures that minimize noise should be studied. A vertical takeoff and landing (VTOL) capability likely reduces population exposed on the arrival and departure portions of the procedure, but there might be new noise annoyance created in the VTOL transition stage (from ascent to cruise, and from cruise to descent) that has not been studied yet. Predicting these noise effects for the urban air mobility (vehicles) that depend on this ability is currently extremely difficult.

Dispersing Operations: Air traffic control today uses technology that concentrates routes to increase operations, efficiency, safety, and predictability. But any concentration has a potential of escalating community annoyance. Dispersing operations, especially over noise-sensitive areas, can be part of a solution, yet it has to be studied carefully, so it does not create a new noise hot spot somewhere else.

Alternating Routes: The concentration of routes exposes communities to repeated noise-dose events, and by alternating high usage routes (especially preferential routes or optimized arrival/departure procedures), we can control the amount of noise exposure.

Hovering: Limiting the amount of time any aircraft can hover or circle in any area can help reduce noise-dose exposure. Before we can ascertain the effectiveness of this measure, additional research on the acoustic footprint and frequencies while hovering should be conducted.

6.4. Operating Restrictions

Although we identify several operating restrictions, we are skeptical as to the feasibility of these due to governing laws and policies currently in place to mitigate aircraft noise. Some of the operating restrictions may be inherently inconsistent with existing laws in the United States [24]. In particular, the adoption of operating restrictions may be subject to the Airport Noise and Capacity Act of 1990 (ANCA) which limits any restrictions on price, route, or service for commercial operations. We discuss this further in the governance section of this paper.

Curfews: Noise curfews can restrict aircraft operation during specific hours of the day. Exceptions would most likely be required for public safety and emergency aircraft. Due to ANCA policy, it is highly unlikely that this would take effect in the United States. Some US airports have grandfathered nighttime noise curfews, and any new restrictions are currently impossible. In contrast, European legislation allows airports to impose curfews to mitigate noise exposure.

Movement limits: The total number of UAS operations in a given area can be effectively capped by limiting the number of flights to a particular location, whether a vertiport or a front yard used for delivering packages. This is analogous to "slot control" limits at certain airports, which cap the number of takeoffs or landings each hour, generally to prevent taxiway and runway congestion. But imposing such limits on UAS operations may have unintended effects. For example, a weekly limit on the number of UAS package deliveries to a given address would require the customer, who may not fully understand the policy, to factor the delivery quota into purchasing decisions. Should a customer use one of her two allotted UAS slots in a week for a new phone charger? What if that person unexpectedly and urgently needs something else at the end of the week, but has already used up her permitted slots? One person's benefit from a fast delivery option risks disturbing others. Therefore, the overarching intent and value of such operations should be considered in setting such policies.

Noise Quotas: A total number of operations can be limited for each operator and each VTOL area. The period can be anywhere from daily, weekly, monthly or yearly quotas. Operators could also be assessed a surcharge, fee or penalty for operations that exceed their quotas.

Non-Addition Rules: These rules can be used to prohibit specific new UAS types based on noise certification standards.

Nature of flights: Non-scheduled flights or flights without a plan can be restricted to use specific areas. Specifically, areas surrounding future vertiports would likely need to be clear of other UAS traffic to ensure the safety of increased operations confined to a small area. However, we expect that many UAS flights won't follow a regular schedule, which would make these types of restrictions unfeasible.

Enforcing Restrictions and Limitations: To ensure compliance with operating restrictions and limitations, a series of steps can be implemented. Geofencing can be used to restrict aircraft in a specific area. UAS operations can be monitored at all times and enforced with fines. Repeat offenders can have escalated restrictions. Any progressive restrictions should be planned and coordinated with all stakeholders to give adequate time to operators to adjust. Importantly, the use of such mechanisms assumes that there are well-established UAS registration, identification and tracking methods. Depending on the country, most of these requirements are works-in-progress and not defined in regulation yet.

6.5. Land use planning and management

Achieving Compatible Land Use: An operator's base of operations can present a significant increase in traffic confined to a small area, and these zones need to be planned and managed carefully to ensure they fit into our environment. Some UAS operators are proposing VTOL hubs on top of parking garages, highway interchanges, and other infrastructure close to the communities they intend to serve [28]. While this has many benefits for the communities using the system, the growth of such operations is going to depend upon local and national governments using their legal authorities to designate land use based on noise exposure. Although new propulsion systems are promising much lower noise footprints, the estimated frequency of operations might present a challenge. One of the reasons new airports are not being built is because of the noise pollution and environmental impacts, and the legislative challenges in overcoming those impacts [29].

Noise-Sensitive Areas: Many operators desire to fly directly from point A to point B [30]. This makes sense due to the flexibility of not being constrained to airports or roads, time efficiency, and reduced costs. But that might not always be possible. Small general aviation and large jet aircraft eventually climb high enough that their ground noise footprint reaches zero. Many UAS missions, on the other hand, will be operating consistently in airspace below 1,000 feet AGL, which increases the potential for noise annoyance. Schools, parks, hospitals, places of worship and other noise-sensitive areas might need to be classified as limited or no-fly zones up to a certain altitude. Additionally, en-route traffic might need to be confined to industrial and commercial areas as well as existing road infrastructure. It is up to the airspace regulator to provide guidance and set standards on how to define and classify noise-sensitive areas. Taken to the extreme, policies that allow generous buffers around and above noise-sensitive areas may effectively close off large amounts of airspace to UAS operations, concentrating them around the edges of those areas. That increased density may not only increase the noise footprint for people beneath those regions, but also poses a potential risk of exceeding airspace capacity and reducing the margin of safety for those operations. The effect would be the opposite of dispersing flights, one of the noise mitigation measures discussed above.

6.6. Managing Community Annoyance

In setting UAS operating guidelines, it is vital for the industry to engage early with potentially affected communities, building relationships and trust through a transparent process. Operationally, this may lead to changes in design and optimization of efficiency but would deliver invaluable returns in the long-term for all stakeholders. For UAS operations at scale, operators cannot rely on regulators to socialize the technology or wait until a community gets used to it. It is in the operators' best interest to lead the conversation. This section contains examples of best practices, based on ICAO case studies of busy air traffic metropolitan areas.

Noise Problem Topics: ICAO Circular 351 identified the most common aviation noise problem topics as general operations concerns ("Why do you need to fly over my house?"), projected growth and capacity expansion needs (increase of operations), changes to airport infrastructure (building a new runway or terminal), and airspace changes (new routes, concentration of flights) [39]. These are the topics operators and regulators most frequently engage in with the community. We speculate these topics might be similar once urban air mobility takes off.

Best Practices: The following are best practices used by aviation stakeholders when engaging with communities:

- Being proactive
- Using a well-planned strategic approach
- Continuous engagement
- Open and transparent exchange of information as the means for building trust ensuring the process is all-inclusive and collaborative
- Managing expectations of all stakeholders
- Using new technologies to provide different ways to present information and interact with the community [39].

Managing stakeholder expectations is vital to effective communication: Establishing common terminology is critical. Such as: what is a significant impact? Aviation authorities have mostly defined terminology and metrics, while the community can simply perceive it as a few night awakenings due to aircraft overflights. There are plenty of challenges ahead as stakeholders typically understand or care mostly about their viewpoints. To manage expectations successfully, acknowledging the issues upfront with clear and transparent communication is needed.

Informed Decision Making: Decision-making in aircraft noise management and operations enhancement programs are often not data-driven. Because noise is perceived differently by each person, it can be difficult to discern how communities are affected. Using data and predictive analysis, potential issues can be identified before the communities raise them. Noise is a complex and subjective problem. Data can be leveraged to make better-informed decisions, communicate effectively and influence actionable outcomes [39].

Thorough community understanding: When advocating for user acceptance of a large number of UAS operations, noise is not only about the acoustical metrics. Instead, a thorough understanding of communities is needed to manage the UAS noise strategy. Communities affected by aircraft noise are increasingly more informed, organized and expect well-thought-out answers and faster actionable outcomes.

Community engagement tools: When a community feels empowered with data for insights into their problems, this eventually builds tolerance and acceptance. Good governance policies might allow users to see who operates a specific UAS, its altitude, aircraft type, and direction of flight. These tools are available for aircraft today and can provide a sense of control for the affected community.

Successful tools for a collaborative approach and successful engagement include modeling, simulations, and other personalized dashboard visualizations. They can be used to educate and effectively describe airspace procedure changes. Websites, emails, electronic surveys and online forums are mediums that can enable more efficient and effective outreach by providing general information, reports, and explanation of various initiatives [39]. But just as important as communicating with residents is providing opportunities for communities to provide feedback and see that their concerns are addressed through adjustments to operating guidelines.

7. Governance

UAS noise strategy cannot be managed without proper policies in place. In the past, aircraft noise problems have led to operational limitations and opposition to expansion. Addressing aircraft noise is essential to ensuring long-term sustainability. Uncoordinated or insufficient policy can lead to a restricted or a decreased set of roles for UAS operations [2]. Although no noise impact studies have been conducted, the ICAO Circular 328 on UAS lists noise as one of the environmental compliance standards, while the FAA's UAS integration roadmap does not include any mention of noise [34].

Throughout this paper we mostly discuss noise initiatives, metrics and regulation in context to United States and Europe as they seem to be the leading areas in aviation noise research and policy formation. Nevertheless, aviation noise is a global concern. Other areas of the world have adopted similar strategies and ICAO guidelines on noise mitigation measures and benefit from the global aircraft fleet reduction.

7.1. Aviation Noise Regulation

In most jurisdictions, the airspace regulator's primary concern is to ensure airspace safety and efficiency. Although regulators have established quantitative noise measures to minimize aircraft noise impacts, they need to be balanced with operational safety and efficiency.

In the United States, the FAA serves as both the country's aviation regulator and its air navigation service provider (ANSP). Local jurisdictions have limited authority to control how the airspace above them gets used, and must either work with the FAA or encourage Congress to mandate that the FAA take additional factors into account in its regulatory processes.

The practical implications of this become apparent when evaluating the rollout of large-scale airspace changes (Section 7.2) without first gathering input from affected communities. UAS operators should be aware of the risk this top-down approach likewise poses in scaling UAS operations.

In contrast, the regulatory bodies in European Union member states must generally satisfy a broader set of requirements in balancing noise mitigation measures with airport capacity constraints. This is codified in EU Regulation 598/2014, which applies ICAO's "Balanced Approach" to managing aviation noise [41].

If industry is willing to work with affected communities from the start and show the willingness to compromise on slightly longer routes or tailored restrictions on types and hours of operation, communities may ultimately be more receptive to increasing the numbers of operations, rather than confronting those operators through lawsuits, congressional action, and overly restrictive rule-making.

7.2. Case Study: FAA NextGen Implementation

NextGen is a continuous effort in the United States to modernize airspace to meet air traffic growth. Many of the same airspace management procedures are part of the Single European Sky initiative. A suite of solutions is a significant change to the national airspace system (NAS) that has not seen many operational changes since its inception. Specifically, the FAA is transitioning from ground radar-based to satellite-based navigation to increase safety, predictability and reduce delays. UASs will share information using digital communications, so all users of the system are aware of other users' precise locations [34].

The procedural enhancement of NextGen is shown in the following graphic depicting the same three paths, but each flown with different navigational equipment [36]. The shaded gray area represents the accuracy or reliability of the navigational equipment. The legacy route on the far left is flown using ground-based navigational aids and is considered the least efficient method concerning costs and flight time. On the other hand, noise impact on the ground might not be as significant because aircraft can be anywhere in the gray shaded area to be considered "on course." Aircraft flying the RNAV and RNP procedures, however, are better optimized and allow for higher efficiency and accuracy of operations. As a result of these technological advances, routes have become more concentrated. This causes greater annoyance to people living below these routes. Although the routes are in the majority of cases direct overlays of the legacy procedures, there is notably less dispersion as well as minor lateral and vertical changes.

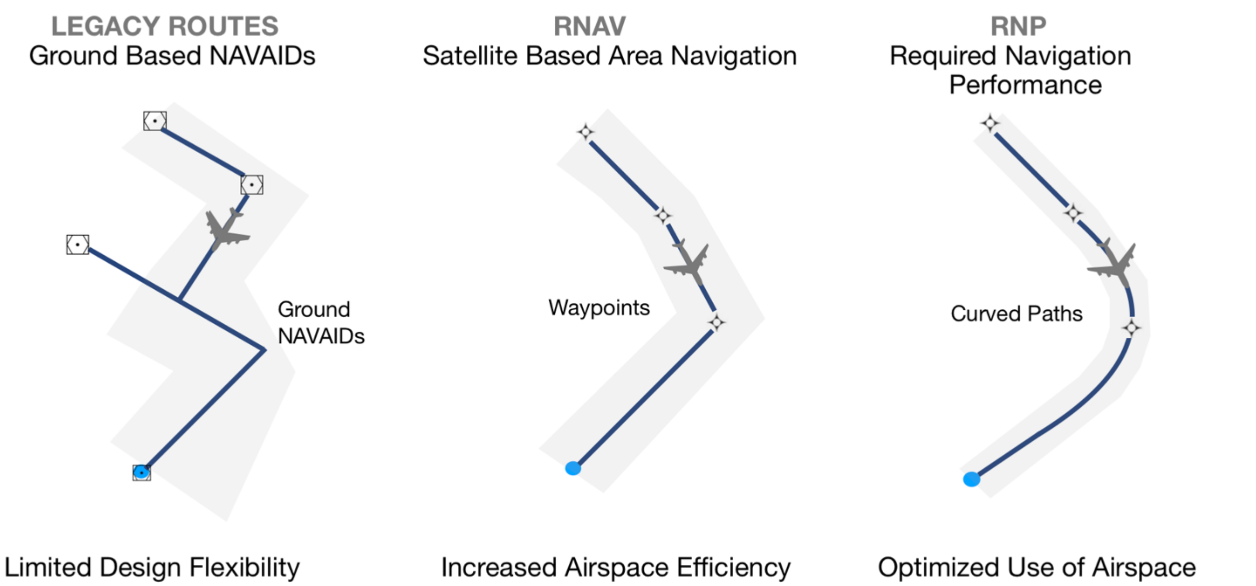

Figure 11. Increasing precision of air navigation equipment results not only in smoother and more efficient routes, but also decreased lateral deviation and dispersion, concentrating flights over a narrower region.

Although no studies have been completed, the general assumption is that due to route concentration, we now have fewer people who are moderately or less annoyed and more people who are highly annoyed. The route concentration is evident in the below flight track density

Legacy routes (pre-metroplex) RNAV and RNP (post-metroplex)

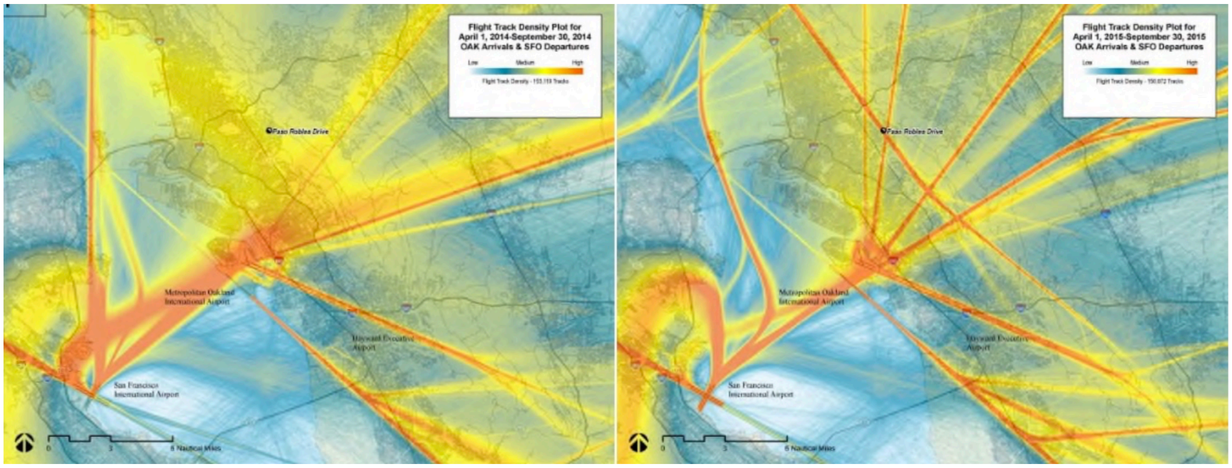

Figure 12. The implementation of RNAV arrival and departure procedures in the San Francisco Bay Area resulted in channelization of flight paths over areas where a similar number of flights had been much more spread out due to vectoring and conventional procedure precision.

analysis of San Francisco International Airport departures to the East and Oakland International Airport downwind arrivals.

The FAA found no significant environmental impact as a result of airspace improvements and therefore did not conduct environmental assessments. The community response to the newly concentrated routes was unexpected. Due to social and political pressures, Congress has become involved to help alleviate some of the new noise disturbance and attempt to make up for the FAA's failures to engage with communities. Specifically, Congress is directing FAA to address community noise concerns, assess community involvement in NextGen Projects, update noise exposure maps and conduct studies on health impacts, and aircraft stages among many other requests [38].

Envisioning the number of flight paths and the variety of UAS types, any UAS traffic management system (UTM) should have flexibility and scalability to resolve bottlenecks in a matter of days, rather than months or even years as currently occurs. However, unless there is a favorable policy in place defining the mitigation criteria to alleviate noise, current practices are unlikely to change. Crowd-sourced governance that better leverages the community's collective knowledge is essential because aircraft noise disturbance is a personal and a sensitive problem to the communities. Information sharing can help build trust through transparency.

8. Conclusions

We identified stakeholders and their roles and emphasized the importance of active collaboration and transparent communication. The success of conversations that take place today will help define the future of UAS operations. Omitting comprehensive noise studies from the assessment process means denying that the noise concerns exist. This can lead to a reactive rather than a proactive approach of mitigating noise and is sometimes still a practice today, as seen with the FAA NextGen projects.

Noise pollution is an environmental risk factor that affects regulation and can impact the UAS growth. If not managed properly, adverse community response can result in social and political pressures, which can lead to operational difficulties and limited or restricted expansion of UAS. Although UAS noise is expected to be lower than other transportation modes, due to the proximity and frequency of operations, it is likely to become an annoyance. Those who plan for UAS to gain widespread community acceptance based on the idea that they will produce no more annoyance than the equivalent amount of traffic noise, may not be correct [15]. Recent dose-response curves show higher annoyance to aircraft, and this is likely to be the same for UAS, if not even higher.

Although it is challenging to predict the effects of UAS noise accurately, as most studies evaluate the impacts based on conceptual design and ideas, there are lessons we can learn from managing aircraft noise. Stakeholders need to plan for sustainable growth that continuously reduces the population exposed to noise while increasing operations. It is unrealistic to expect that the current use of quantitative metrics used by FAA is going to enable high-density UAS operations. It is essential to research and adopt new metrics that will allow UAS growth with public-wide support. Further, by adopting a data-driven approach that identifies possible constraints in simulations and noise modeling, we can help predict community response. With this in mind, a UTM platform needs to be flexible and scalable to accommodate operations safely and efficiently, while also incorporating noise reduction procedures.

To gain widespread community support, tolerance can be built by active engagement and collaboration with all stakeholders. We introduced approaches in this paper that can help relieve some of the annoyance and allow further growth of UASs. ICAO’s balanced approach to mitigating noise provides a reasonable framework for doing this as it incorporates the reduction of noise at source, land use-planning, and management, operational limitations and restrictions and last but not least, community engagement strategy. Depending upon regulatory framework a number of these tools and strategies can be deployed to help scale the UAS operations.

9. Future Work

There is significantly more research needed in addressing the UAS noise pollution to understand the scope and impact of the UAS. Specifically, further work is suggested in:

- A comprehensive examination of noise from UASes
- Reduction of UAS rotor noise
- Defining UAS noise certification and other standards as they relate to noise mitigation
- Identifying best quantifiable noise metrics and researching new ones
- Modeling of high-density UAS noise footprint
- Ensuring flexibility of traffic management platform to implement noise abatement procedures
- Identifying noise hot spots in traffic management platforms
- Studying effects of route concentration, and repeated close-proximity noise events
- Conducting community noise exposure survey studies on annoyance levels and mitigation effects
- Generating noise dose-response curves of UASes and comparing it to other transportation modes
- Addressing community involvement
- Researching compounding effects of aircraft, road and UAS noise

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