

CHALLENGES IN ADVANCED AIR MOBILITY NOISE PREDICTION - FROM SOURCE TO PERCEPTION

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Abstract

Advanced air mobility (AAM) concepts introduce new challenges for aircraft noise and annoyance prediction due to low-altitude operations, proximity to populated areas, and highly distributed propulsion systems. Traditional aircraft noise prediction and assessment methods are insufficient to capture the acoustic characteristics of AAM aircraft and operations. This review paper provides an overview of key challenges in AAM noise and annoyance prediction, covering the complete chain from noise generation to human perception. The requirements from the view of a three-stage evaluation approach, assessing noise at the component, total aircraft, and fleet or airport scenario level are derived. At the component level, limitations of current tonal and broadband propeller noise models are discussed. At the aircraft level, the integration of multiple propulsion units and installation effects are identified as a major challenge. Furthermore, complex trajectories and routing in urban environments are considered. The final scenario stage is the assessment of multiple aircraft, heterogeneous fleets and varying business cases. Also the relevance of psychoacoustic metrics and perception-based assessment methods are highlighted, emphasising the need for integrated, perception-oriented noise prediction frameworks for urban and regional AAM applications.

Keywords: Advanced Air Mobility, Noise, Perception, Prediction

1. Introduction

Advanced Air Mobility (AAM) concepts promise new possibilities for urban and regional transportation but pose serious challenges with respect to social acceptance [1]. Compared to conventional aircraft, AAM aircraft operate in close proximity to populated areas, exhibit highly distributed and transient noise sources, and encompass a wide range of configurations, from small unmanned aircraft systems (UAS) to manned multicopters, lift-and-cruise aircraft with open or ducted rotors acting as lifting and propulsive systems (also known as electric vertical take-off and landing aircraft, eVTOL) and their interaction effects. Thereby, established noise prediction and assessment methodologies are insufficient to capture the full complexity of AAM in operation as highlighted in the gap analysis of recent studies, such as [2, 3, 4, 5] conducted by researchers of the International Forum for Aviation Research (IFAR).

This paper provides a structured overview of the key challenges in AAM noise prediction, spanning the entire chain from noise generation to human perception. A three-stage evaluation approach is adopted, addressing noise at the component, total aircraft, and scenario levels. At the component level, current modeling capabilities and limitations for tonal and broadband propeller noise are

discussed. The aircraft level is dominated by the installation effects of the propulsion system. Furthermore, the influence of complex flight trajectories, urban environments, and routing strategies on community noise exposure is examined. The scenario is finally compiled by tailoring trajectories, operational restrictions and business decisions. Beyond physical metrics like the sound pressure levels, the paper emphasises the growing importance of psychoacoustic metrics and perception-based assessment methods for AAM.

1.1 Applications and Configurations

Advanced air mobility (AAM), also referred to as innovative air mobility (IAM) in Europe, covers a wide range of applications and operations, from urban to regional air mobility. Compared to conventional air transport, air vehicles envisioned in AAM concepts are lighter, using (mostly) electrical propulsion and are therefore quieter and more suited to operate near urban or residential areas. On the other hand, technological developments are still limiting the range and size of the vehicles.
This new class of vehicles is well suited for the following transportation needs in these regional or urban areas [1, 6, 7]:

- **Emergency and public services.** The most publicly accepted application of AAM is the use for emergency or public services [8]. In particular, medical services are considered the launching application that has the most support among both (local) governments and citizens where they are introduced. The need for quick delivery of medical goods, such as blood bags or samples or organ transport, is evident and may even be life-saving [9, 10].
- **Cargo transport.** Cargo transport will also be a promising application to ensure quick delivery of goods in congested or remote areas. Depending of the size of the anticipated cargo, these can be close to homes (such as door-to-door package delivery services) or to and from warehouses, distribution centres or shops. Noise annoyance can have an impact on public acceptance, but due to the limited number of ongoing operations in Europe there is little evidence to quantify its impact with the measured noise levels [11]. See also [12] as an example of the ongoing discussion in Ireland.
- **Passenger transport.** The most visible application for AAM in the near future is the use of eVTOLs for the quick transport of passengers, preferably in congested metropolises [13, 14]. Typical launching operations will be from an international airport towards the city centre, or connecting two close cities or city areas. Private ownership is not foreseen, as first services are expected to be premium (air) taxi services. There may be some challenges in relation to public acceptability, although eVTOLs are expected to be quieter and less polluting than helicopters that they may replace.

The payload, the required range, and the type of application defines the mission to be flown. This mission subsequently defines the requirements for the aircraft configuration that is able to execute this mission, e.g., see Ref. [15]. In general, two different types of configurations can be distinguished. First, configurations without wings, such as helicopters and multicopters. Benefit of this configuration is a full vertical take-off and landing, providing flexibility to the start and landing locations and the routing of the vehicle itself. It also allows for hovering operations in case of congestion or delays. Second, configurations with wings that carry the aircraft weight during cruise flight. The advantage of this configuration is that less energy is needed in the cruise phase, increasing the range and/or reducing the weight because of reduced need for an energy carrier. In the second category, a wide range of wing–propeller combinations can be found. However, each combination involves trade-offs in terms of complexity, aerodynamic efficiency, operational capability, stability, cost, noise and other disciplines. Consequently, no single configuration dominates across all operational scenarios.
The most common configurations are listed below:

- **Multicopters:**
  Propellers generate the entire lift of the aircraft, and no aerodynamic lifting surfaces are used. Example: EHang, Volocopter.

- **Lift-and-cruise configurations:**
  Dedicated propellers provide lift during VTOL, while a separate propulsion is used for cruise flight. Example: Beta Alia-250, Eve Air Mobility.

- **Vectored-thrust (or tilt-rotor) configurations:**
  The same propellers are used for VTOL and (some or all) are tilted to generate thrust during wing-borne cruise flight. Example: Joby aviation, Archer.

Helicopters are the traditional configuration for AAM operations but they will not be counted into the advanced or innovative air mobility sector for the scope of this paper.

1.2 Three-Level Approach and Associated Challenges

A structured three-level approach, e.g., as established by DLR [16, 17], can be applied to fully address the challenges of AAM noise and annoyance prediction in a consistent and scalable manner. Such an approach ensures to capture all effects and interdependencies that arise from an introduction of novel technology, i.e., starting from a single vehicle comprised of certain components up to a large fleet scenario [17].

- **Component level:**
  At the component level, individual noise sources such as propellers or rotors are analysed under representative operating conditions. The focus is put on identifying dominant noise mechanisms and on developing and validating suitable source models. Unsteady or transient operating conditions of the propulsion system must be systematically evaluated to identify critical flight states. Hereby, the focus lies on the emission without application of any noise metric or descriptor. At the component level, the application of a system-level noise descriptor is not feasible; thus, an effective perceived noise level (EPNL) cannot be defined per component. Evaluation of noise descriptors is foreseen when the focus lies on the immission of an entire vehicle or a fleet.

- **Aircraft level:**
  At the aircraft level, component noise sources and findings from the component level are integrated into a complete aircraft model. Installation effects, source interactions, and unsteady operating conditions are taken into account to assess the overall aircraft noise emission and immission. At this level, noise descriptors can be applied to the entire vehicle immission. Standard noise descriptors, e.g., A-weighted maximum sound level $L_{A,max}$, sound exposure level L_{AE}, and EPNL. Furthermore, at this level, advanced and novel noise descriptors as described in Section 4. can be evaluated. Noise immission of the entire vehicle can also be converted into audible sound files for listening tests to account for the actual noise perception as described in Section 3.. Such psychoacoustic assessment has been demonstrated in the literature by various groups, e.g., see Ref. [18]. Total aircraft noise is assessed along entire flight trajectories that are resolved under trimmed flight conditions using realistic flight-mechanical representations of the aircraft. Total aircraft noise levels are evaluated across the entire flight envelope while accounting for relevant variations in parameters for a specific vehicle, e.g. rotorcraft depent on angle of attack, flight Mach number, rotor revolutions per minute (RPM), and nacelle angle whereas conventional fixed-wing aircraft would require information on configurational setting, thrust setting, and flight speed. The overall assessment at the aircraft level includes both single observer locations, e.g., certification situation, and large grids of observers, e.g., to assess noise contour areas.

- **Scenario level:**
  At the scenario level, the contribution of a fleet of aircraft is evaluated along realistic flight trajectories and operational procedures. Here, novel aircraft might be mixed into the existing fleet in order to evaluate the impact on the overall noise levels in long-term scenarios. At this point, typically only strongly simplified and averaged descriptors are evaluated, e.g., time-averaged and weighted noise levels such as the Day–Evening–Night level L_{DEN} that is integrated over longer time periods. Even if the novel aircraft and technology is known and can be described

on a high level of detail at the component and aircraft level, the scenario level requires strong simplifications in order to be compatible to the available data of the existing fleet, which are usually based on Noise-Power Distance (NPD) data. Computational costs have to be low enough to handle the overall amount of vehicles and flight routes which only allows for simplified assessment methods.
In the case of scenarios composed of new types of aircraft entirely, which might be the future of urban air traffic, the choice of noise model and metric might be re-evaluated. Depending on calculation capacities and targeted traffic density, low fidelity options might be considered. Furthermore, computational costs have to be low enough to handle the overall amount of vehicles and flight routes which only allows for simplified assessment methods.

Noise-modelling challenges arise at all identified analysis levels [17] and will be further discussed in the following sections. At the component level, the primary challenge lies in accurately representing specific vehicle aspects. For example, rotorcraft would require a dedicated assessment and understanding of the boundary-layer state along the rotor chord at different radial locations. Assuming a fully attached boundary layer in low-fidelity semi-analytical predictions of turbulent boundary-layer trailing-edge noise can lead to erroneous results, since most semi-empirical wall-pressure models adopted in these approaches are derived from measurements obtained under attached-flow conditions. Similarly, inaccurate prediction of the separation point in high-fidelity Computational Fluid Dynamics (CFD) simulations can result in incorrect estimates of the turbulent fluctuations near the trailing edge, thereby compromising noise predictions. At locally low Reynolds numbers, the boundary layer may enter a transitional regime and develop laminar separation bubbles. These phenomena are difficult to predict using scale-resolving CFD methods and can significantly influence high-frequency broadband noise levels. Another component-level challenge concerns the generation of high-fidelity experimental data for validation purposes, as recirculating flow within test chambers can contaminate noise measurements [19].
At the aircraft level, the main challenges are associated with modelling aerodynamic and installation effects. Analytical prediction methods generally lack the flexibility required to capture effects arising from specific geometrical features, whereas computational approaches must accurately predict the convection of wakes and sound with minimal numerical dissipation. This capability is essential for reliable prediction of aerodynamic and acoustic installation effects in multi-rotor configurations. Additional challenges relate to overall weight (reduction) of the vehicle to improve overall performance including noise impact, and in case of passenger transport, the isolation of aircraft noise inside the cabin to improve passenger comfort. At the aircraft level, the total vehicle is modelled under varying operating conditions as experienced along any realistic flight. This adds additional challenges in predicting the noise, especially if the operational situation strongly changes the noise emission, e.g., appearance of additional and new noise sources under a new operating condition as can be experienced for rotorcraft if installation effects occur. Another important aspect at the aircraft level is the selection of an appropriate noise descriptor. Limitation to a single descriptor shall be avoided at all means. For example, only evaluating A-weighted noise levels will introduce a strong bias by removing low-frequency content from further evaluation. For some cases, where low-frequent contribution at higher noise levels is experienced, e.g., propeller tonal contribution at low frequencies, the limitation to only A-weighted levels will result in erroneous interpretation of the results. For the exemplary propeller aircraft with its low-frequency content, the A-weighting could lead to a very wrong judgement of the vehicle as a low-noise vehicle. It is essential to apply multiple noise descriptors, i.e., also including different weighting functions and tone corrections, in order to yield a realistic and complete picture for any total aircraft noise assessment.
At scenario level the choice of a good noise indicator presents equally a challenge. While certain integrated metrics might be well suited for commercial air traffic around airports, they need to be reevaluated for AAM traffic assessment. Potentially sparse flyover numbers (before operations scale up), shorter emergence duration, etc. imply new questions on integration duration and choice of threshold values. As previously mentioned, strong simplifications in the modeling stage are necessary to account for dense traffic, a long period of time, an important area covered, or all three combined. Certain hypotheses have also to be considered for the calculation of propagation in the

urban environment, which has to be added to noise emission calculation times, for AAM traffic scenarios that can occur over densely populated areas. It is of utmost importance to understand the implications of simplifications at the scenario level. This stage enables the assessment of scenario noise immission and provides the basis for noise-aware routing and operational optimisation. The predicted scenario noise levels are then used to evaluate long-term noise annoyance and health implications for exposed communities [20]. Whether for purposes of health implication evaluation or a step below, traffic management, it is important to consider and account for implicit uncertainties in the predicted noise levels, but also in the operational concepts. The uncertainty linked to the various already existing and future aircraft technologies, combined with their specific operational conditions can strongly impact the robustness and validity of any post-processed assessment. Today the uncertainties and variability of aircraft and operational concepts make scenario assessments tricky and lead to a focus on single mission analysis. Considering the expected growth in AAM operations, elevated noise levels are anticipated around vertiports. Vertiports are typically situated in urban areas and have densely populated environments near them. The proximity of these grounds can limit the public embracement of AAM operations, posing additional regulatory and planning challenges. Finally, overall airspace performance is directly influenced by noise regulations. Operational limits lead to reduced flexibility in routing and timing of flights over the day or night. This reduced operational flexibility can consequently increase the complexity of air traffic management, diminish the overall efficiency of air traffic operations, and necessitate more stringent noise mitigation strategies.

2. Noise Modeling

The key challenges associated with AAM noise modelling and the design of low-noise propellers for AAM aircraft have been discussed extensively in the literature [21, 22, 23]. At the component level, tonal noise from open rotors operating under nominally uniform inflow conditions can be predicted using steady aerodynamic loads obtained from Blade Element Momentum Theory (BEMT) [24, 25], coupled with compact-source acoustic analogy formulations [26]. Extensions to unsteady tonal noise prediction can be achieved through unsteady aerodynamic response models capable of estimating the fluctuating forces along the blade span caused by cyclic variations of the angle of attack in non-axial inflow conditions [27, 28], or by accounting for periodic blade–arm interaction effects [29].

Broadband rotor-noise prediction typically relies on semi-analytical trailing-edge and leading-edge noise formulations. However, these approaches require detailed knowledge of turbulent-flow statistics within the boundary layer near the trailing edge, or within the rotor inflow, and are therefore not fully predictive, relying instead on assumptions or precursor CFD simulations. In transitional boundary-layer regimes, laminar separation phenomena may arise, leading to high-frequency tonal components and/or spectral broadening [24]. These effects remain difficult both to characterize experimentally [30] and to predict numerically [31, 32]. Furthermore, one largely unexplored source of annoyance is associated with continuous rotor-RPM variations, which introduce additional challenges for accurate noise prediction.

At the total aircraft level, accurate prediction of rotor–rotor and rotor–airframe interaction effects becomes essential. These interactions may be aerodynamic in nature, such as the impingement of front-rotor wakes on downstream rotors [33], tip-vortex interactions in side-by-side rotor configurations [34], interactions between airframe wakes and downstream rotors [35], or conversely between rotor wakes and airframe components [36]. Additional challenges arise from rotor inflow distortions induced by nearby airframe structures, such as supporting arms [29]. Another important phenomenon is the intermittent fountain flow generated by side-by-side rotors operating in ground effect, which can produce low-frequency modulation and elevated noise levels [37].

Acoustic installation effects are instead associated with the scattering of rotor noise by airframe components, particularly when the acoustic wavelength becomes sufficiently small relative to the size of the reflecting surfaces. While such effects are generally negligible for conventional helicopters [26], they can become significant in tilt-rotor configurations [38].

At this level, the primary modelling challenge arises from the strong dependence of aerodynamic interaction noise on the operating condition. In multi-rotor eVTOL configurations, even more than in conventional helicopters, dominant noise mechanisms are often linked to rotor–rotor aerodynamic in-

teractions and therefore depend strongly on parameters such as flight Mach number, angle of attack, side-slip angle, nacelle tilt angle, and rotor RPMs. Covering the entire flight envelope may therefore require the evaluation of thousands of operating conditions and the computation of an equally large number of noise hemispheres as precursor data for trajectory-based footprint calculations [39].

Because a full aerodynamic trim and aeroacoustic characterization of the complete flight envelope is computationally infeasible, multi-fidelity methodologies currently represent the only viable approach for operational eVTOL noise prediction [40]. In these frameworks: (i) the aero-mechanical trim problem is solved using multi-body dynamics combined with simplified aerodynamic models based on precomputed CFD-derived lookup tables for airframe aerodynamic coefficients and BEMT-derived rotor performance coefficients; (ii) representative missions are simulated to sample the flight envelope; (iii) the resulting flight conditions are statistically down-sampled to retain the most representative and acoustically critical operating points; (iv) selected operating conditions are analysed using high-fidelity aerodynamic and aeroacoustic simulations to populate a Noise Hemisphere Database (NHD) and improve the low-fidelity prediction models; and (v) noise footprints for arbitrary trajectories within the same flight envelope are evaluated by combining flight-dynamics calculations with on-the-fly interpolation and extrapolation of the NHD data to ground observers [39].

Likely even more important, although still largely unexplored, is the effect of continuous RPM variations introduced by flight-control systems to maintain hover position under perturbed inflow conditions. These challenges should ultimately be reflected in eVTOL-specific certification procedures, whose definition represents a major technological and regulatory challenge [41]. When looking at scenario level, one could take example of the current procedure for commercial aircraft, where NPD data are used for fleet noise predictions. However, the establishment of said NPD database for AAM seems challenging due to very complex flight and aircraft configurations [42].

Several major scenario-level challenges need to be considered. The scenario concepts can significantly vary from inner-city to regional transportation concepts. It is unclear, how the airspace structure and traffic routing will be organized. Any scenario assessment at this point is not only limited by the lack of total aircraft noise prediction capabilities but more so by not having defined operational and routing concepts. The final selection of such concepts would also depend on the flight performance of the actual AAM vehicles which are still under investigation.

Furthermore, the impact of the urban environment on operational procedures, noise emission and noise propagation is significant. Accurate prediction of community-noise metrics requires accounting for sound scattering by buildings [43], steady and unsteady convective effects associated with wind flow around urban structures [44, 45, 46, 47], and the ingestion of atmospheric turbulence by the rotors [48]. In addition, the inclusion of local background noise information becomes essential.

3. Noise Perception

Noise perception in AAM operations is influenced by temporal, spectral, and spatial characteristics of the noise [49], as well as operational factors. Unsteady operating conditions, pronounced tonal components, and installation effects can significantly increase perceived annoyance compared to steady-state or isolated noise sources. With the earlier described variety of aircraft configuration for eVTOLs, it makes it more challenging to estimate the noise footprint of an early design. For this purpose, auralization techniques [50] would be needed to predict all earlier mentioned acoustical effects, including interactions and installation effects, in order to test human reactions to the generated noise of new eVTOL designs. Therefore, perceptual assessment must go beyond purely energy-based metrics to more accurately reflect human response.

In addition, noise annoyance should be assessed in a holistic manner, accounting not only for aircraft-generated noise but also for the existing ambient sound environment. Recent research has developed evidence and psychoacoustic models to account for the effect of the existing ambient sound on the overall noise annoyance produced by AAM operations [51]. Due to the close proximity to the ground and operations over urban communities, interactions between AAM noise and background noise can strongly influence perception and annoyance [52, 53]. Other aspects, not yet discussed, are the influence of subjective, personal or other non-acoustical factors that influence peoples' reaction towards the sound of an eVTOL [54, 55]. These factors can include demographic characteristics such as age,

personal factors such as noise sensitivity, as well as psychological factors such as attitude towards drones, perceived visual pollution and fear. Additionally, general attitudes towards aerospace and the perceived usefulness of applications (e.g., utilising air taxis or receiving expedited drone deliveries) can influence acceptability of AAM operations. This highlights the need for integrated assessment approaches that combine source noise prediction, auralisation and soundscapes in perception studies.

Furthermore, there is a growing need for auralisation tools that enable psychoacoustic assessment based on realistic, time-domain sound representations [56]. Such tools allow controlled listening experiments, facilitate subjective evaluation under representative operational scenarios, and support the validation and calibration of psychoacoustic models [57]. Auralisation techniques can provide a pathway for developing and refining perceptually relevant metrics that extend beyond traditional descriptors.

Recent work, such as the development of psychoacoustic prediction models for short-term annoyance to UAS [53], demonstrates the importance of considering additional contextual and acoustic factors (see also [52]). These studies show that perceived annoyance is influenced not only by intrinsic sound properties (e.g., sound intensity and sound quality attributes) but also by ambient acoustic environments and operational characteristics, including the number of flight events. Such findings highlight that future generalised AAM noise metrics should integrate both psychoacoustic attributes and operational/contextual variables to better represent real-world human response.

4. Psychoacoustic Metrics

Conventionally, aviation noise assessment has relied on compact, sound level-based indicators designed to support regulation and large-scale environmental evaluation. These indicators reduce the inherently complex temporal and spectral characteristics of aircraft noise into single-number descriptors, typically derived through energy averaging. Among these, A-weighted sound pressure level metrics, such as the equivalent continuous level L_{Aeq} and sound exposure level L_{AE}, remain the most widely applied. The A-weighting function provides a simplified representation of human auditory sensitivity by approximating equal-loudness contours, thereby offering a practical, though coarse, proxy for perceived loudness. In parallel, “perceived noise” metrics, including perceived noise level (PNL) [58] and its certification-oriented forms such as tone-corrected (PNLT) and effective perceived noise level (EPNL), extend this concept by incorporating level-dependent spectral weighting and tonal penalties (in addition to correction for event duration) [59]. These metrics have proved effective in standardisation and policy contexts due to their relative simplicity and consistency, and they continue to underpin aircraft noise certification and epidemiological studies.

Despite their practical advantages, these traditional approaches exhibit important shortcomings when applied to emerging AAM concepts. The reduction of complex acoustic signals to energy-based quantities inherently limits their ability to differentiate between sounds that possess distinct perceptual characteristics [60]. This limitation is particularly evident for AAM vehicles, whose noise signatures often include strong tonal components (including multiple blade passing frequencies and harmonics), elevated high-frequency content, and pronounced temporal variability arising from multiple electric propulsion systems. Although certain extensions to conventional metrics introduce tonal corrections (e.g. EPNL) or account for repeated events, these remain only partial solutions and do not fully represent the perceptual impact of such sounds. Because AAM aircraft operate close to the ground, their complex noise signatures may be more or less audible depending on ambient sound conditions, which can provide varying levels of acoustic masking. Torija et al. [61] showed that in soundscapes dominated by road traffic noise, the addition of UAS noise led to only minor changes in perceived loudness, annoyance, and pleasantness. In contrast, in quieter environments with less traffic noise, the same UAS noise significantly increased perceived loudness and annoyance while reducing pleasantness. As a result, reliance on conventional descriptors alone may obscure key differences in how AAM noise is experienced by listeners, highlighting the need for more perceptually grounded approaches.

Psychoacoustic metrics offer a more detailed and perceptually grounded alternative by explicitly modelling auditory processing and quantifying specific sound attributes relevant to human perception [62]. Psychoacoustic metrics can provide a quantitative link between physical noise characteristics

and human annoyance [63]. These metrics provide a more holistic assessment of a sound stimulus by accounting for different sound features relevant for noise perception. Metrics such as loudness N, sharpness S, roughness R, fluctuation strength F, tonality K and impulsiveness I are essential to capture perceptual effects that are not adequately represented by conventional sound pressure level–based measures [53]. The appropriate selection and combination of these metrics strongly depend on the specific AAM operating conditions and noise characteristics.

Psychoacoustic metrics are typically derived from auditory models that represent sound transmission through the outer, middle, and inner ear, often implemented as filter banks approximating the frequency selectivity of the cochlea. The resulting band-limited signals are then processed to quantify perceptual attributes. While standardised models exist (e.g., Zwicker [64], Moore–Glasberg [65] or Sottek [66] loudness formulations), important challenges remain regarding model selection, temporal aggregation, binaural effects, and computational cost. Furthermore, considerable variability exists in how time-varying psychoacoustic metrics are reduced to single descriptors (e.g., exceedance levels or power averages), with limited consensus on best practice [67].

Composite psychoacoustic indicators, such as Zwicker's unbiased annoyance (UA) [68] or the Widmann psychoacoustic annoyance (PA) [69], attempt to combine multiple sound quality metrics into a single predictor of perceived annoyance. Although these approaches provide improved correlation with subjective response compared to level-based metrics, their applicability to AAM remains uncertain due to differences in sound characteristics and the dependence of model coefficients on specific datasets and metric implementations. Torija et al. [70] and Boucher et al. [71] have extended Widmann's PA to UAS rotor noise and UAM vehicle noise respectively.

While there has been a significant progress in understanding of links between psychoacoustic metrics and novel AAM noise sources [53], a generalized psychoacoustic indicator is still required that can be robustly applied within aircraft design and optimization processes, enabling annoyance-based design decisions at early development stages.

At present, specific noise limits for AAM operations are still under development, and regulatory frameworks remain incomplete. Existing certification approaches largely rely on standards designed for conventional aircraft, which may not adequately account for the distinct acoustic characteristics and increased annoyance associated with AAM noise. For instance, EASA has published a range of maximum allowable EPNL (takeoff, flyover, landing) and L_{Aeq} (hover) for eVTOLs depending on maximum takeoff mass [72]. Recent reviews highlight a lack of dedicated and harmonised noise metrics, limits, and certification procedures tailored to these novel vehicles, identifying this as a key research and regulatory gap that must be addressed to enable widespread deployment [49]. In practice, authorities are often addressing AAM noise on a case-by-case basis while more comprehensive standards and limits are being developed at international level.

5. AAM Traffic Management

Noise routing and mapping as assessed in level 3 – the scenario level – describe the spatial and temporal distribution of noise along representative AAM flight trajectories. Trajectory design, operational procedures, and altitude profiles have a significant influence on ground-level noise exposure [73]. It has to be noted that the final traffic scenarios will heavily depend on the flight performance of the individual aircraft of a mixed fleet. From a known or assumed fleet mix, noise footprints can be derived and used as input for assessing impact on humans and wildlife. Exemplary, Lieb et al. [74] initially calculate A-weighted sound pressure exposure levels for all trajectories of a simulated drone delivery scenario over a certain region and distribute them over a regular immission grid. With propagated immissions, geometric and atmospheric damping (according to International Organization for Standardization (ISO) standards such as ISO 9613-2), finally A-weighted equivalent continuous sound levels are derived and plotted for the region. The results give an approximate magnitude of AAM community noise. Remaining limitations in [74] are the not considered reflections from ground or buildings as well as local conditions such as weather or humidity. Furthermore, psychoacoustic effects and metrics as described above have not yet been taken into account, so the assessment is only preliminary.

Other projects have looked into scenario analyses. Simic et al. [75], for example, have described a performance framework for the assessment of the social and environmental impact of AAM through

focus areas like noise, visual pollution, and privacy concerns, followed by access and equity, economic aspect, emissions, public safety, and impact on wildlife. For each identified focus area, performance indicators were defined along with the several cross-cutting areas for a geographical, temporal, demographic, socioeconomic, and behavioral resolution. For the fleet noise impact calculation semi-empirical noise models were used, linked to raytracing urban environment propagation [76].
Especially around frequently used start and landing points, so called vertiports or droneports, higher levels of noise exposure can be expected. Preis et al. [77] conclude vertiport noise to be a significant operational consideration for implementation of AAM. For 18 different eVTOL designs they analyze scenarios in three primary areas: vertiport throughput, rotor noise, and flight performance as measured by speed, range, and payload. Rotor noise is modeled using blade element momentum theory here. Preis et al. conclude that multicopter configurations generally perform better in noise-limited environments but are limited in flight performance compared to other configurations. Overall, these findings underline the need of advanced propagation tools for novel aircraft types operational in urban environment.
Overall airspace performance is dependant of several factors as shown in seminar works such as Gonzales et al. [78]. Their framework links airspace performance to metrics like operational efficiency, safety, energy usage, and community noise exposure, that are governed by performance envelopes of heterogeneous mixed fleets. In other works, see e.g. [79, 80], noise sensitive or densely populated areas are circumvented in AAM corridor design to minimize negative community reactions from the beginning. Farazi et al. [81] assess population noise exposure based on the level of sound generated, the number of people impacted and the duration of the impact.
Finally, accurate noise routing models are essential for assessing community impact and for enabling noise-aware flight planning. However, noise assessment procedures that consider psychoacoustic effects are yet to be established for AAM [82]. A remaining challenge is the very limited amount of published acoustic data for novel AAM aircraft types. A positive example are recorded flight tests of the Joby aircraft. Thai et al. [83] compare computational aeroacoustics predictions for two steady, level flight conditions with measured noise levels of the prototype aircraft while Schatzmann et al. [84] perform wind tunnel tests on the Joby rotor configuration.
As mentioned previously, the high variety of parameters playing into AAM fleet scenarios, makes it challenging to predict viable future scenario options and their noise impact. The choice of aircraft configurations, associated with their flight and manoeuvre capabilities, and therefore routing restrictions is crucial. Especially the fact that uncountable different aircraft types might operate simultaneously. Flight objective and purpose have an important impact on operational choices as well. Another challenge is added by the complexity of certain urban specificities such as urban canyons, time related specificities like day/night flights or the intermodal analysis that is necessary to neutrally assess the impact of AAM noise on population.

6. Conclusion

This paper outlines the key steps required for reliable AAM noise and annoyance prediction and highlights their implications for aircraft design.

- First, noise modeling is feasible using mid- and high-fidelity approaches. However, major challenges in modeling are the interaction and the broadband noise. Reduced-order models must be derived for application in early design phases and scenario level analyses. All modeling approaches require systematic validation against wind-tunnel measurements and full-scale flight test data.
- Second, psychoacoustic metrics are required to represent noise annoyance (and other relevant perceptual variables) across different AAM aircraft concepts and operating conditions. These metrics must be robust and suitable for integration into multidisciplinary design and optimization frameworks.
- Third, the perception of AAM aircraft among residents requires further analysis to identify critical operating conditions, assess the limitations of existing aircraft noise metrics, and evaluate the applicability of psychoacoustic metrics as well as their potential improvements.

- Fourth, annoyance-based routing and trajectory optimisation methods must be developed to mitigate the impact of AAM operations on communities along flight paths.
- Finally and most important, at this point no general "AAM noise assessment" can be conducted reliably since the overall operational concepts are still vague. Novel aircraft configurations under development with their flight performance and hence their noise characteristics vary widely. Thus, current assessments remain focused on single trajectories, while scenario assessment is still vague due to the remaining uncertainties in the operational concepts.

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