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# Urban Air Mobility Noise: 2025 Update on Current Practice, Gaps, and Recommendations

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# Executive Summary

Advanced air mobility (AAM) is an aviation concept that involves leveraging emerging technologies, business models, and other capabilities to bring aviation into the regular life experiences of the general public. There is no universally agreed-upon definition of AAM, but it has been described by NASA as "safe, sustainable, affordable, and accessible aviation for transformational local and intraregional missions." Urban air mobility (UAM) is the sector of AAM that focuses on short-range, "local" missions around metropolitan areas, which have an urban area at their core. UAM is generally envisioned to leverage heliports or novel vertiports located throughout metropolitan areas as airspace access points to provide rapid transportation capabilities, even in locations with extreme road congestion. Along with the many anticipated benefits of UAM, there will be potential noise issues that must be addressed. In 2018, NASA formed an Urban Air Mobility Noise Working Group (UNWG) to assemble noise experts from industry, universities, and government agencies to identify, discuss, and address UAM noise issues.

This paper presents an update to the 2020 UNWG white paper entitled, "Urban Air Mobility Noise: Current Practice, Gaps, and Recommendations [1]," in which a set of high-level goals was developed to address barriers associated with UAM noise that may hamper their entry into service. Much has changed since that paper was published. The purpose of this paper, therefore, is to i) develop an updated set of high-level goals, ii) reassess the current practice in the four areas of interest (Tools Development and Experimental Validation, Ground and Flight Testing, Human Response and Metrics, and Regulation and Policy), iii) identify gaps between the current practice and the updated high-level goals, and iv) assess progress on the prior recommendations and make new recommendations to close those gaps. The 2025 high-level goals are presented below. The consolidated set of abridged recommendations for each area of interest is provided in Appendix F, whereas the unabridged versions are provided in Sections 2.4, 3.4, 4.4, and 5.4, respectively.

Unless otherwise noted, the content herein represents a consensus view of the UNWG participants. Any opinions, findings, conclusions, or recommendations expressed in this report are those of the contributors and do not necessarily reflect the views of their companies, organizations, or government agencies.

### 2025 High-Level Goals

The 2020 goals were directed at future activities of the UNWG. The 2025 goals replace the 2020 goals and are directed at the community at large. They are:

HLG-2025-1. Develop noise and performance tools suitable for application to perceptually low-noise (relative to existing ambient levels) vehicle designs and operations that are validated using laboratory and flight test data.

HLG-2025-2. Develop and assess noise-reduction technologies that are validated using laboratory and flight test data.

HLG-2025-3. Develop vehicle noise and operations databases and tools to support the establishment of standards for UAM aircraft type certification and community noise assessment.

HLG-2025-4. Develop noise-abatement landing and takeoff (LTO) procedures for piloted and automated operations in coordination with UAM vehicle manufacturers and operators.

HLG-2025-5. Develop long-term exposure-response relationship(s) by evaluating multiple metrics, including, but not limited to, day-night average sound level ($L_{dn}$) and percentage highly annoyed (%HA), to help inform policy at the national, regional, and local levels.

HLG-2025-6. Encourage effective communication of noise effects, along with proactive engagement with the public.

HLG-2025-7. Establish and execute a systematic plan for capturing and sharing lessons learned across all areas related to UAM noise.

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# 1 Introduction

*Written contributions were provided by (in alphabetical order) Jeremy Bain (Joby Aviation), Jordan Cluts (NASA), Bill He (FAA), Brenda Henderson (NASA), Siddhartha Krishnamurthy (NASA), Leonard Lopes (NASA), Philip McCarthy (NRC), Roberto Merino-Martinez (TU Delft), Michael Patterson (NASA), Stephen Rizzi (NASA), and Royce Snider (Bell Flight).*

## 1.1 Urban Air Mobility Background

"Advanced Air Mobility" (AAM) is an aviation concept that involves leveraging emerging technologies, business models, and other capabilities to bring aviation into the regular-life experiences of the general public. There is no universally agreed-upon definition of AAM, but the International Civil Aviation Organization (ICAO) is developing an AAM Vision document that will provide some degree of standardized description when it is finalized. AAM has been described by the National Aeronautics and Space Administration (NASA) as "safe, sustainable, affordable, and accessible aviation for transformational local and intraregional missions" [2] and generally all agree that it includes both Urban Air Mobility (UAM) and Regional Air Mobility (RAM). In fact, the U.S. Congress, through the Federal Aviation Administration (FAA) Reauthorization Act of 2024 [3], has defined AAM as "a transportation system that is comprised of urban air mobility and regional air mobility using manned or unmanned aircraft."

UAM focuses on short-range, "local" missions around metropolitan areas, which have an urban area at their core. UAM is generally envisioned to leverage heliports or novel vertiports located throughout metropolitan areas as airspace access points to provide rapid transportation capabilities, including locations with extreme road congestion. RAM consists of intraregional missions, which are generally of greater ranges than UAM missions and are not necessarily centered on urban areas. Intraregional is used here to refer to the NASA AAM definition. Because the size of a region is arbitrary, using intraregional emphasizes that the term "regional" in RAM refers to distances shorter than traditionally inferred by other uses of the term regional in aviation, such as regional jets. There are no specific strict limits for the ranges of UAM or RAM missions, but generally, UAM missions are on the order of tens of miles and RAM missions on the order of 50-500 miles. Both UAM and RAM include cargo and passenger transportation and are anticipated to rely on advancements in technology and operations to shift missions, which are often performed on the ground today, into the air.

The main areas of ambiguity around the scope of AAM pertain to the breadth of aircraft sizes and mission types. Specifically, there are differing viewpoints on the inclusion of aerial work missions and small unmanned aircraft systems (sUAS) within the scope of AAM. Aerial work comprises aviation missions for "specialized services" other than passenger or cargo transportation [4]. Examples include banner towing, traffic monitoring, aerial photography, and wildland fire monitoring. These missions involve moving something into the air to perform a useful function, and the aircraft typically concludes its mission at its origin point. The FAA Reauthorization Act of 2024 definition limits aircraft for AAM to those with maximum takeoff weights of greater than 1320 lbs. (roughly 600 kg), which excludes sUAS, and dictates that these aircraft move "passengers or property by air between 2 points" [3], which essentially precludes aerial work missions. The 1320 lb. limit stems from what was, prior to the release of the Modernization of Special Airworthiness Certification (MOSAIC) rule [5], the upper weight limit of a light sport aircraft. In contrast, the NASA definition, which dates to 2020, incorporates aircraft of any size and aerial work missions. The differences in definitions stem, in part, from the regulatory focus of the FAA versus the technological focus of the NASA.

The European Union (EU) Aviation Safety Agency (EASA) has defined its own terms, Innovative Air Mobility (IAM) and Innovative Aerial Services (IAS), in lieu of AAM that explicitly differentiate aerial work from passenger and cargo transportation missions. Specifically, IAM refers to multimodal transportation of passengers and cargo and IAS focuses on aerial work missions [6].

The ICAO Committee on Aviation Environmental Protection (CAEP), in which the FAA and the EASA participate, has adopted the term "emerging technology aircraft" to include sUAS, electric vertical takeoff and landing (eVTOL), and other AAM aircraft, for which no existing chapter of ICAO Annex 16 Volume 1 [7] can be used for noise certification (see Section 5).

Regardless of where the bounds of the AAM space are defined, AAM is envisioned to include a wide variety of missions that can be performed by a range of aircraft types. In its Advanced Air Mobility National Strategy [8] and accompanying comprehensive plan [9], the U.S. Government-wide Advanced Air Mobility Interagency Working Group describes many potential mission types within AAM, including access to national airports, travel over difficult terrain, emergency response, air taxi, cargo operations, and more. A variety of aircraft featuring advanced technologies, such as electric propulsion systems, high levels of automation, and distributed propulsion, are believed to provide sufficiently low costs and increased performance capabilities compared to traditional aircraft platforms to help enable these many missions. AAM aircraft include eVTOL aircraft, Unmanned Aircraft Systems (UAS), hybrid-electric aircraft with short takeoff and landing (STOL) capability, and electric conventional takeoff and landing (eCTOL) airplanes, to name a few. A visual depiction of some notional AAM missions and aircraft assuming a broad AAM definition is provided in Figure 1.

UAM has received significant attention over the last decade and is the primary focus of this paper. Note, however, that many of the concepts discussed in this paper are also applicable to other portions of AAM. Visions for UAM and how operations may be performed are provided in sources like the Uber Elevate White Paper [10], the UAM Maturity Level 4 Vision Concept of Operations (ConOps) [11], and the UAM ConOps v2.0 [12] from the FAA. Many sources and discussions of UAM focus on passenger transportation so as to resonate with the general public and highlight the high levels of safety necessary for UAM to become widely adopted. Consequently, much of the discussion in this paper will emphasize passenger transport, but the concepts discussed will be applicable to effectively any UAM mission type.

For UAM to provide advantages over existing transportation options, UAM aircraft must take off and land from locations closer to where people live, play, and work than aviation has historically seen. Although the most time could be saved with true "Jetsons-style" operations in which aircraft fly directly from initial origin to final destination, there will likely be a limited set of dedicated takeoff and landing locations for UAM aircraft, which are typically called vertiports, in a given metropolitan (metro) area. Visions for the number of potential vertiports in a metro area vary, but generally they are discussed as ranging from only a few, particularly for early operations, to tens or, in some further-future visions, hundreds. These vertiports may be located on top of buildings, in repurposed parking lots, at existing airports, on top of parking garages, or at other "greenfield" sites. In this construct, UAM transportation is inherently multimodal—i.e., individuals will travel both on the ground and in the air for portions of their journey. In a UAM trip, a traveler would move on the ground from their initial origin to a vertiport, perhaps by walking, biking, riding in a car, or by some other means. Then, the individual would fly in a UAM aircraft from one vertiport to another before taking another ground mode to their destination. The multimodal nature of UAM travel will require integration into the broader transportation landscape of a metro area.

Although there is no universal definition of a UAM mission and each mission will vary in specifics, some general characteristics of these missions include payloads on the order of a few passengers or equivalent cargo, ranges on the order of a few tens of miles, cruise flight at altitudes of approximately 1,000 feet to a few thousand feet above ground level, and cruise speeds on the order of 100 knots. Some proposed requirements for UAM missions and aircraft can be found in Refs. [13] and [14].

Figure 1: A graphical depiction of some potential advanced air mobility missions and notional aircraft.

## 1.2 An Overview of UAM Aircraft

There are many types of air vehicles being considered and developed for UAM. Many envision vertical takeoff and landing (VTOL) aircraft, while others propose STOL aircraft. Some are pursuing manned (also referred to as crewed) aircraft, while others propose unmanned (also referred to as uncrewed) aircraft. These aircraft range in size from a single passenger, or even smaller for cargo transport missions, up to approximately nine passengers or equivalent weight of cargo. This subsection discusses the proposed aircraft configurations and propulsion systems.

### 1.2.1 Electric and Electrified Vertical Takeoff and Landing Aircraft

Despite the differing views, eVTOL aircraft are most commonly proposed for UAM. Fundamentally, the eVTOL moniker implies that an aircraft is electric, storing all the required energy in batteries, and can take off and land vertically. The "e" in eVTOL can also be considered to mean "electrified"—i.e., the aircraft may not employ a pure battery-electric propulsion system architecture but leverage electricity in some other form of hybrid architecture, generally to distribute power among multiple propulsive devices (which are referred to generically as propulsors). Electrified aircraft propulsion architectures include, but are not limited to, parallel hybrid electric, series hybrid electric, hydrogen fuel cell, solid oxide fuel cell, and turboelectric. Regardless of the specific architecture, electrification enables distributed propulsion—more specifically, distributed electric propulsion (DEP)—and potentially synergistic airframe propulsion interaction, which can provide benefits in aircraft design and performance [15,16]. Among these potential benefits is reduced noise, which may be achieved through many strategies, including, but not limited to, positioning propulsors in locations that enable acoustic shielding, use of lower-noise electric motors rather than conventional engines, and low-tip-speed propulsors (which can be achieved through distributing disk area over multiple propulsors to lower individual blade radii and/or leveraging the ability of electric motors to produce high torque at a range of speeds). A major reason these eVTOL aircraft are proposed for UAM is that they are generally believed to enable lower operating costs than conventionally fueled VTOL aircraft, and cost is a major driver of potential UAM demand.

Many eVTOL aircraft are classified as powered-lift aircraft, meaning they can take off and land vertically, but rely on fixed wings for lift in other phases of flight. Note that the formal definition of powered-lift is "a heavier-than-air aircraft capable of vertical takeoff, vertical landing, and low-speed flight that depends principally on engine-driven lift devices or engine thrust for lift during these flight regimes and on nonrotating airfoil(s) for lift during horizontal flight" [17]. Some example powered-lift configurations include Multi-Tiltrotor, Tiltwing, and Lift + Cruise aircraft, see Figure 2. Generally, these powered-lift aircraft are less efficient in vertical flight compared to conventional rotorcraft but are more efficient and can fly faster in cruise flight than conventional rotorcraft. These characteristics are believed to be advantageous due to the limited hover requirements in UAM missions and the desire to transport passengers and cargo quickly. That said, some eVTOL aircraft are rotorcraft that rely directly on their propulsors for lift in all flight phases. The formal definition of a rotorcraft is "a heavier-than-air aircraft that depends principally for its support in flight on the lift generated by one or more rotors" [17]. The most proposed rotorcraft eVTOL configuration is a multicopter, which is also referred to as multirotor. The Vertical Flight Society has an extensive list of proposed eVTOL aircraft in its eVTOL Aircraft Directory [18].

### 1.2.2 Non-eVTOL Aircraft

Other types of VTOL aircraft apart from electrified aircraft are also being considered for UAM, most notably highly automated conventional helicopters. Although it can be argued that existing charter helicopter operations around major cities can be considered a form of UAM, the UAM term is generally understood to imply a future state with more widespread operations than occur with these existing operations. These more widespread operations indicative of UAM may be enabled, some contend, with highly automated or fully autonomous conventional rotorcraft, which could reduce costs and increase effective payload capacity (by removing a pilot from the aircraft). Even if costs can be reduced with automation or autonomy, the same noise challenges that affect existing rotorcraft operations will be encountered. Due to other literature and efforts focused on conventional rotorcraft noise, such conventional rotorcraft are not the focus of this paper.

Some contend that vertical takeoff and landing capabilities are not inherently required for UAM operations and instead propose STOL aircraft (sometimes called super-STOL or extreme-STOL aircraft) that can take off and land in less than a few hundred feet. STOL operations were contemplated with civil tiltrotor aircraft in the 1980s-1990s to enable increased range and/or payload capacity in conventional tiltrotors, as evidenced in part by the now-canceled FAA Advisory Circular 150/5390-3 [19] for Vertiport Design that included consideration for elongated touchdown and lift-off surfaces (TLOFs). Similar sorts of elongated TLOFs in novel vertiports could provide locations for STOL aircraft operations in the future, although such concepts have not yet resurfaced in more recent guidance for vertiport design from the FAA [20]. The feasibility of future STOL-based operations has also been studied, indicating potentially feasible markets [21-24].

As with eVTOL aircraft, electrification of the propulsion system is viewed as an enabler for most novel STOL aircraft, and they rely on some form of DEP for their STOL capabilities. Proponents of these aircraft point to the potential for cost reductions in comparison to eVTOL aircraft [25], but others point to the likely more limited takeoff and landing locations and inability to hover (e.g., for air traffic management reasons) as major drawbacks of such designs for UAM operations. Such STOL aircraft are not the primary focus for this paper, but many of the issues explored for VTOL aircraft with DEP will be relevant for understanding the noise produced by STOL aircraft.

### 1.2.3 General Classification and Reference Aircraft

Work on vertical and/or short takeoff and landing (V/STOL) aircraft has been of interest in aviation for decades, and many proposed configurations aim to achieve VTOL and/or STOL capabilities. There has been some effort to classify the many different types of V/STOL aircraft configurations over time, with recent updates incorporating eVTOL aircraft by Newman and Lawless [26-28]. Generally, these classifications categorize configurations based on how lift is produced for vertical flight (or very-low-speed forward flight) and how thrust is produced in forward flight. Ultimately, there are many potential configurations that have been proposed leveraging various technologies and integration strategies, and several configuration types are currently under development for UAM operations.

Details of specific UAM aircraft are generally proprietary to the companies that are developing them. To provide publicly available reference aircraft that are representative of many of the proposed UAM configurations under development, the NASA Revolutionary Vertical Lift Technology (RVLT) Project defined the set of reference vehicles shown in Figure 2 [29]. These aircraft provide common, non-proprietary means to examine design trades, evaluate technologies and the technology impact on mission requirements, simulate vehicle operations, and more. Details about the RVLT reference vehicles are found in Refs. [29-35]. The aircraft in this figure are divided into powered-lift aircraft on the left side and rotorcraft on the right side.

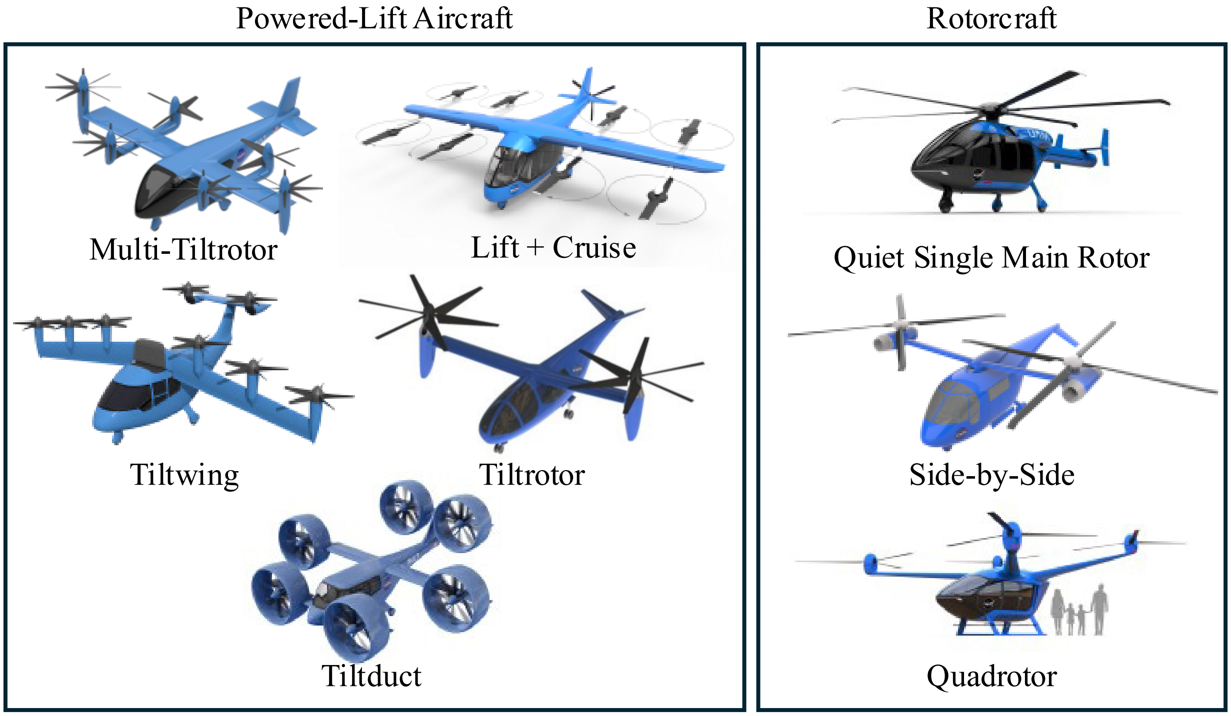

Figure 2: NASA UAM reference vehicles [29] divided by statutory definitions [17].

Although not an exhaustive sampling of the design space being considered for UAM, the aircraft in Figure 2 provide a reasonable overview of some of the major characteristics of proposed UAM aircraft. The aircraft on the right side of the figure have their rotors oriented around a fixed rotational axis and produce the necessary thrust (and other forces and moments necessary for flight) primarily from their rotors. There are also variants of the Quadrotor configuration that do not feature cyclic blade pitch control of the rotors but rather leverage changes in rotor rotational speed for control. Regardless, these rotorcraft rely on their propulsors for lift, thrust, and control in all phases of flight. In contrast, the powered-lift aircraft on the left side of the figure rely on their propulsors for lift in vertical flight but have wings for lift in forward flight. Each of these configurations apart from the Lift + Cruise design has some form of tilting of the propulsors to achieve vertical flight: the Multi-Tiltrotor and Tiltrotor rotate multiple rotors, the Tiltwing rotates its main wing and tail propulsors, and the Tiltduct rotates its ducted propulsors. The Lift + Cruise aircraft has lifting propulsors that are connected by booms to the wing, and each of these "lifters" maintains a fixed rotational axis. Thrust for forward flight is provided by a separate propeller, and the lifters are stopped and aligned with the airflow for forward flight to reduce drag. Many of these aircraft are non-traditional, including multiple propulsors that interact with one another and with fixed lifting surfaces, and thus possess different acoustic characteristics than traditional aircraft.

## 1.3 UAM Noise

### 1.3.1 How Does it Differ from Other Aviation Noise?

UAM vehicle operations will introduce a new source of noise into the environment and, therefore, will alter existing soundscapes. Vertiports will likely be in populated areas where UAM noise levels will be highest due to low-altitude flight and LTO operations. This will likely result in some communities being newly exposed to aviation noise and others experiencing an added layer of noise alongside pre-existing aircraft and other transportation operations and facilities, whether individually or in combination (e.g., road, rail, or helipads). While the noise level of UAM vehicles may be lower than that of other aviation noise sources, the potentially large number of operations sets them apart from existing aircraft operations. Furthermore, one UAM vehicle design may have entirely different acoustic characteristics from those of another vehicle in terms of spectral and temporal characteristics. This is less the case for other aviation noise sources, within the same class of aircraft. This variability may limit the utility of commonly used sound exposure metrics, such as the A-weighted equivalent continuous sound level ($L_{Aeq}$), which correlate well when comparing changes, e.g., in the number or magnitude of otherwise similar operational sound events. Different sound metrics may be needed to compare the human response of these new vehicles to that due to existing aircraft operations, because their sound differs in more ways than just amplitude.

Historically, changes in noise over a populated area have been met with resistance. This resistance can be in the form of noise complaints, which can potentially call for more strict local noise ordinances that can restrict vertiport siting. In fact, recent studies on societal acceptance of UAM by the EASA [36] found that noise was the second greatest public concern, after safety, regarding the introduction of UAM across Europe. Thus, community engagement will be important to keep the public informed.

### 1.3.2 Managing UAM Noise

The internationally agreed-upon balanced approach to aircraft noise management at international airports includes four main elements: reduction of noise at the source, land use planning and management, noise abatement operational procedures, and operational restrictions on aircraft [37]. The management of UAM noise will likely include these same elements, however the way they are implemented, and the roles and responsibilities for doing so, may differ from those employed for most of existing commercial aviation.

Successful aircraft source noise reduction comes from cooperation among government agencies, industry, and universities. Noise reduction technology development and demonstration of technical feasibility are very important, and mesh well with the development of noise certification standards, including noise limits, testing methods, and procedures. In the recent past, there has been much research directed at the prediction and reduction of eVTOL noise [38]. This includes the assessment of existing tools for application to UAM, the development of experimental methods and databases for tool validation, and efforts to improve methods and tools when deficiencies are found. Acoustic flight test data remain limited, but opportunities to collect more data are on the horizon with several manufacturers now seeking type certification. In parallel with noise research, efforts are underway to develop international noise standards and recommended practices (SARPs) by CAEP, Working Group 1 - Noise. Until those standards are developed and adopted by national regulators, manufacturers seeking noise certification may be faced with differing noise regulations in different countries. Nevertheless, reduction of noise at the source through a combination of effective low-noise design features and the noise certification rules, even if interim, are expected to permit launches of commercial operations in the U.S. and abroad as early as 2026.

Land use planning and management provides a way to minimize noise exposure for populations near airports through preventative measures, e.g., zoning, if possible. Land use planning guidelines are structured to maintain geographic separation of the effects of airport operations from the encroachment of neighboring community development. However, these guidelines are not always effective, as developments often encroach on airports. The placing of vertiports in densely populated areas presents a new challenge. Community engagement is considered important and effective, especially when a change in noise is introduced to the environment. Appropriate measures of noise exposure that reflect lived experience can potentially provide a consistent standard for meaningful assessment of community noise response. Note that UNWG participants did not reach consensus on a description of the concept of "lived experience" used in this report. Recent laboratory research on human annoyance to short-term UAM noise exposure has provided evidence of dependency on factors beyond the vehicle noise level, e.g., the background sound in which the vehicle operates (see Section 4.2.1.1). Community surveys conducted after operations commence can help refine understanding, improve modeling, guide noise research, and enhance low-noise aircraft operations.

Noise abatement operational procedures are those procedures, either automated or pilot-initiated, that change the flight operation to reduce the noise on the ground. For safety reasons, noise abatement procedures are usually voluntary. In the case of large commercial aircraft, such procedures might entail different takeoff and landing procedures. In the case of helicopters, low-noise techniques, like those encouraged in the Fly Neighborly Program [39], allow pilots to reduce community noise exposure. Noise abatement procedures for piloted and autonomous UAM operations may be difficult to generalize due to the wide variety of UAM vehicle concepts. Future acoustic flight test measurements of operational UAM vehicles will help identify low-noise flight procedures.

Operational restrictions are considered a last resort and applied after the other three elements have been implemented. Examples of operational restrictions include curfews and noise caps.

## 1.4 UAM Noise Working Group

The UAM Noise Working Group (UNWG) was formed in 2018 to address the need for the quiet design and operation of UAM vehicles. The UNWG participants include nationally and internationally recognized subject matter experts from industry, government agencies, and academia (see Appendix C.2 for participating organizations). The Group is organized into four subgroups addressing the following areas of interest: Tool Development and Experimental Validation, Ground and Flight Testing, Human Response and Metrics, and Regulation and Policy.

The first product released by UNWG was a white paper [1], published in 2020, that addressed current practices, gaps, and recommendations for each of the UNWG subgroup areas of interest. The purpose of this paper is to i) develop an updated set the high-level goals, ii) reassess the current practice in the four areas of interest, iii) identify gaps between the current practice and the updated high-level goals, and iv) both assess progress on the prior recommendations and make new recommendations to close those gaps.

### 1.4.1 Prior (2020) Set of High-Level Goals

In the 2020 white paper [1], each of the four subgroups developed their own set of goals. These were rolled up into the following set of overarching, high-level, goals of the UNWG:

HLG-2020-1. Document noise reduction technologies available for UAM and identify knowledge gaps for each of the four areas of interest (UNWG subgroups).

HLG-2020-2. Assess prediction capabilities for benchmark problems based on an open set of reference vehicle designs using available data.

HLG-2020-3. Assess metrics for audibility and annoyance of single-event vehicle operations using available predicted and measured data.

HLG-2020-4. Define measurement methods/procedures to support noise regulations and assessment of community noise impact, and coordinate with UAM vehicle manufacturers on development of low noise approach and takeoff procedures for piloted and automated operations.

HLG-2020-5. Examine fleet noise impacts through prediction and measurement, and characterize effectiveness of supplemental metrics for audibility and annoyance.

HLG-2020-6. Promote UAM integration into communities through mitigation of fleet noise impacts, and engagement with the public.

### 1.4.2 Updated (2025) Set of High-Level Goals

While the 2020 set of high-levels goals were directed at future activities of the UNWG, the updated 2025 set of high-level goals replacing them are directed at the community at large. They are:

HLG-2025-1. Develop noise and performance tools suitable for application to perceptually low-noise (relative to existing ambient levels) vehicle designs and operations that are validated using laboratory and flight test data.

HLG-2025-2. Develop and assess noise-reduction technologies that are validated using laboratory and flight test data.

HLG-2025-3. Develop vehicle noise and operations databases and tools to support the establishment of standards for UAM aircraft type certification and community noise assessment.

HLG-2025-4. Develop noise-abatement landing and takeoff (LTO) procedures for piloted and automated operations in coordination with UAM vehicle manufacturers and operators.

HLG-2025-5. Develop long-term exposure-response relationship(s) by evaluating multiple metrics, including, but not limited to, day-night average sound level ($L_{dn}$) and percentage highly annoyed (%HA), to help inform policy at the national, regional, and local levels.

HLG-2025-6. Encourage effective communication of noise effects, along with proactive engagement with the public.

HLG-2025-7. Establish and execute a systematic plan for capturing and sharing lessons learned across all areas related to UAM noise.

Throughout this paper, the expression "exposure-response relationship" is used instead of "dose-response relationship" to reinforce the fact that the aircraft noise a population experiences is not a controlled amount of noise, i.e., a dosage. Further, noise exposure may be of short duration, often measured by instantaneous metrics, or long duration, often measured by time-integrated metrics.

## 1.5 Description of Sections

The remainder of this paper is organized along the lines of each of the four UNWG subgroups. Following a brief introduction, each section discusses the current practice, gaps in the current practice, and recommendations to address those gaps to achieve the high-level goals. This paper is not intended to be a complete literature review, although it offers a sufficient number of references to support its assertions.

Each subsection includes an assessment of the 2020 recommendations. A "**Closed**" status indicates a topic has either been superseded by a 2025 recommendation or that sufficient work has been identified to recommend its closure. The "**Closed**" status does not mean additional work will not advance the current understanding. The "**Progress Made**" status indicates that efforts have been identified that progress our understanding, but additional work is recommended. The "**Open**" status indicates that little or no efforts have been identified that address the recommendation.

Unless otherwise noted, the content herein represents a consensus view of the UNWG participants.

# 2 Tool Development and Experimental Validation

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## 2.1 Introduction

This subsection is primarily concerned with noise prediction tools and facility testing in support of UAM vehicle design for compliance with noise certification requirements and assessment of community noise response to UAM operations and addresses topics aligned with recommendations 4.3 and 7.7 in the AAM National Strategy [8]. The analyses typically focus on the prediction of objective metrics and follow (all or part of) a source-path-receiver paradigm, in which source noise emissions are propagated through the atmosphere along a path(s), for reception by the receiver(s). Each element is discussed below, with some emphasis on UAM vehicle source noise due to its unique nature.

### 2.1.1 Source Noise

UAM vehicle source noise differs from that of existing rotorcraft. For vertical lift, it is anticipated that a larger number of rotors will be used for UAM vehicles rather than the one or two rotors used on conventional helicopters and tiltrotors. Unlike conventional rotorcraft, the rotors on some UAM vehicles may operate with variable rotational speed and have lower tip Mach numbers, lower Reynolds numbers, higher rotation rates, and different propulsor configurations and sizes for different missions (e.g., a pusher/tractor propeller for forward flight in combination with rotors for vertical lift and with lower-aspect ratio blade shapes). These features of UAM vehicle rotors will change the frequency content and sound quality metrics of the time-varying rotor noise relative to conventional rotorcraft.

With conventional rotorcraft, blade-vortex interaction (BVI) noise (due to a parallel blade-vortex encounter) can be a dominant source in level flight and is typically a dominant source in descent. For UAM vehicles, BVI noise is possible for the vertical lift or transition segments but should be less dominant than for conventional rotorcraft if the rotor tip speeds are lower. This interaction could be an intra-rotor or an inter-rotor effect (similar to a conventional tandem rotorcraft) due to expected relative rotor placement. In cruise, BVI could be present but less dominant if the propulsors are oriented in a propeller configuration. However, some configurations can have aft propellers that are affected by the wakes of propellers, wings, and other structures that are forward of them. In addition to BVI, turbulence entrained by a tip vortex impinging on the propulsor or a nearby propulsor causes blade-wake interaction (BWI) noise.

BVI and BWI are just two of the potential types of propulsor-propulsor, propulsor-airframe, and propulsor-environment noise-generating interactions associated with UAM vehicles. Some interactions are depicted in Figure 3 and include turbulence ingestion noise (TIN), blade-airframe interaction (BAI), fuselage-wake interaction (FWI), and steady rotor loading. Many other noise sources not depicted below are possible. For example, rotor pairs in a coaxial configuration (both co-rotating and counter-rotating) can have inter-rotor interference, while rotors embedded in ducts will have mutual wake, aerodynamic, and acoustic interference with the internal duct support structures.

UAM vehicle rotors will likely be driven by electric motors and powered by either batteries or hybrid-electric systems. Electric motors are a significant noise source for sUAS [40] and may be an additional noise source for UAM aircraft that is not present in conventional rotorcraft. Hybrid-electric systems could include auxiliary power units or turbine power generators that will have unique noise characteristics.

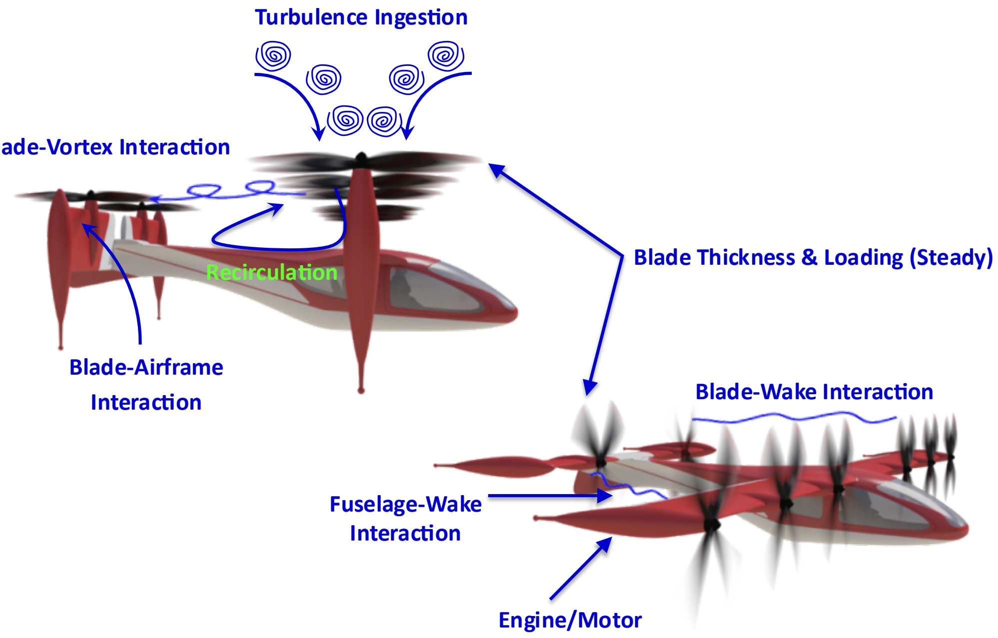

Figure 3: Some potential noise-generating interactions on a UAM vehicle.

### 2.1.2 Sound Propagation

The physics of sound propagation of UAM vehicle noise is no different from that of other vehicles. The operating environments for UAM aircraft will likely include vertiports, urban canyons, and densely populated areas. In these settings, sound propagation will be impacted by the proximity of large buildings, as well as variations in local wind and atmospheric conditions. In addition, the presence of high-turbulence environments, including wakes of buildings and trees, modifies the sound propagation path, resulting in regions of high modulation and sound variability. Challenges associated with UAM vehicle noise measurements in urban landscapes and with auralization of UAM vehicle noise in simulated urban environments are discussed in Sections 3.3.2 and 4.3.1.5, respectively.

It has been proposed that near-term entry-into-service aircraft may take off and land in repurposed environments such as parking lots or rooftops. Future vertiport environments will likely be significantly different from the repurposed ones and from current heliports. These vertiports will likely have a wide range of configurations, be manufactured from an assortment of materials whose impedance properties are less known, and include reflective structures (e.g., buildings). The repurposed environments and newly designed vertiports will result in unique noise propagation challenges.

## 2.2 Current Practice

Accurate acoustic predictions for UAM vehicles require knowledge of the complex flow field around the vehicle, the sound generation caused by that flow field, the propagation of sound to the receiver, and the assessment of perceived noise by the receiver. Computational tools can be used to understand the complex physics in each step of the sequence to the receiver. These tools are validated against experimental data, and experimental data guide the development and improvement of the prediction tools. Thus, there is a synergy between tool development and experimental validation activities that results in the evolution of accurate tools and better experimental capabilities. Sections 2.2.1-2.2.3 explain current state-of-the-art computational tools and experimental capabilities as they are applied to the prediction and assessment of UAM vehicle noise. Section 2.2.4 explains the current state-of-the-art of noise reduction technologies.

### 2.2.1 Source Prediction Tools

Current state-of-the-art practices for the prediction and assessment of UAM noise fall into one of three categories. First, component noise prediction, which includes studying a single component of the full UAM vehicle such as the propulsion system and, typically, an isolated propulsor or possibly a propulsor in the presence of a wing. Component noise prediction facilitates the construction and refinement of noise source models that, when validated with static and/or wind tunnel measurements of similar geometries, can then be used to perform the second category of noise prediction – assessment of the entire vehicle system. System-level analysis includes the calculation of the vehicle performance, mission, and acoustic source generation and propagation (i.e., near and far field) and is used to assess the acoustic performance of the vehicle. Results from system noise predictions are compared to controlled flight test data to assess the accuracy of the simulations. Flight testing is discussed in Section 3. Results of system noise predictions under various flight conditions are leveraged for the third category of prediction and assessment – estimating the human response to UAM vehicles such as human perception and the effect on communities. Human response is addressed in Section 4.

#### 2.2.1.1 Isolated Sources

**Deterministic (Tonal) Sources**

Similar to traditional rotorcraft vehicles, integral forms of the Ffowcs-Williams and Hawkings (FWH) equation [41] are typically used to capture periodic thickness and loading noise from propulsors [42]. Acoustic pressures at defined observer locations are determined using either a permeable or impermeable source surface. The permeable surface typically surrounds the blades and rotates with them or encloses the entire rotor or vehicle and does not rotate (see Figure 4). While this method is relatively simple to implement, spurious signals could arise if the hydrodynamic fluctuations associated with the vortical structures from blade wake and tip vortices traverse the enclosing surface [43]. At the same time, the acoustic sources can suffer from numerical dissipation and dispersion due to the computational scheme used to propagate them between the blades (or other solid surfaces) and the permeable surface. For UAM configurations operating in low-subsonic rotor-/propeller-tip Mach numbers, some volumetric sources, such as those associated with high-speed impulsive noise, may be considered negligible. Under such conditions, it is therefore possible to omit the volume integral term accounting for quadrupole noise in an impermeable formulation and compute surface sources only, thus eliminating the generation of artificial spurious signals. In the case of high tip Mach numbers, where the volume term can no longer be justifiably neglected, it is possible to compute the volume integral restricted to the immediate vicinity of the blades, as the quadrupole contribution is expected to decay quickly away from the body surface. In the following, the impermeable formulation, without the quadrupole term, is considered and, in particular, Formulation 1A of Farassat (F1A), which is well suited for UAM vehicle noise applications [44].

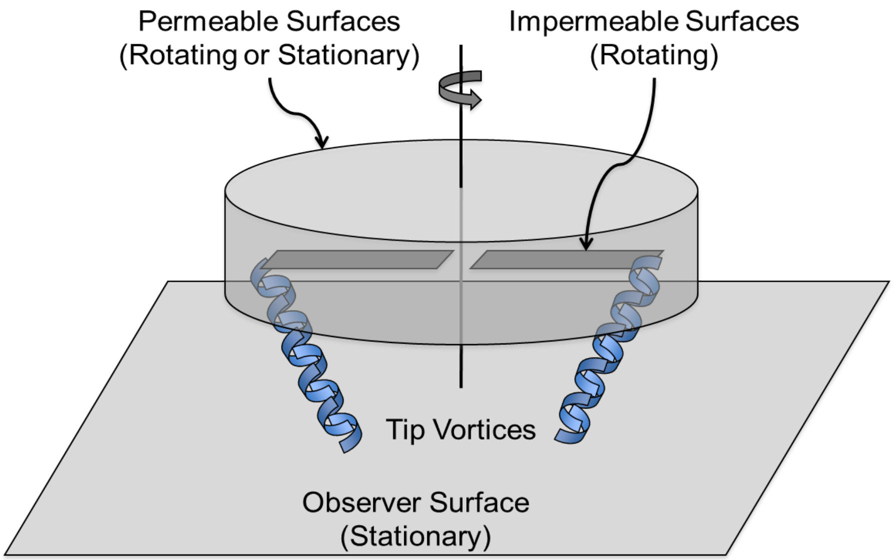

Figure 4: Depiction of permeable and impermeable surfaces for FWH calculation.

"Thickness noise," also called "monopole noise," is related to the air displaced by a body in motion relative to the observer. When the blade geometry and motion are known, thickness noise is accurately predicted. While computations are relatively fast for the full surface blade geometry and motion, even faster (yet still quite accurate) methods using compact thickness models are available for designers [45-47]. The compact thickness models provide computations that are about an order of magnitude faster than those using the full surface and are accurate if there is no violation of the compactness assumptions. Both the full surface and compact methods are commonly available and are in routine use.

"Loading noise," also called "dipole noise," is related to the aerodynamic forces acting on a surface. Loading noise can be caused by unsteady loading of a stationary surface (relative to the observer), steady loading of a surface moving relative to the observer, or a combination of both. Accurate aerodynamic data and surface motion are required for accurate noise predictions. For traditional rotorcraft, aerodynamics and blade motion strongly affect each other and are often coupled during the aerodynamic calculation. A "loose-coupling method" passes aerodynamic and blade-motion data between codes at time intervals that are typically multiples of the blade passage or rotor revolution, often with the assumption of periodicity imposed on the solution. This approach works well when the motion is periodic or can be considered quasi-steady (or quasiperiodic), e.g., for maneuvers when the maneuver time scale is long relative to the rotational time scale of the rotor. "Tight coupling," where aerodynamic and structural data are passed between codes at every time step, has been used in the past for maneuvers where the time-scale assumption for loose coupling is violated. This method is very computationally expensive. For aperiodic cases, a general loose-coupled method is not available, and tight coupling is even more computationally expensive for UAM aircraft relative to traditional rotorcraft due to the vehicle's multiple rotors.

Loading noise may be i) steady periodic, e.g., a rotating blade in uniform inflow, ii) unsteady periodic, e.g., a rotating blade with a time-varying (but periodic) angle of attack, or iii) unsteady aperiodic. If the source is aperiodic, the amount of blade-loading data needed for a far-field acoustic calculation (using F1A) is large. If the source is steady periodic or unsteady periodic, the amount of blade-loading data can be reduced to that of a single blade passage or a single revolution, respectively. The combination of multiple rotors/propellers has the added complication that the summed pressure at the receiver may be aperiodic if the rotors/propellers are asynchronous or operating at different rotational rates from one another. In this case, propagation to a ground observer using a frequency-domain approach becomes problematic, emphasizing the need for time-domain propagation (see Section 2.2.1.2).

BVI noise is a form of impulsive loading noise where the tip vortex from a blade interacts with another blade such that the interaction is parallel, i.e., the vortex axis is nearly parallel to the rear blade leading edge. This interaction can occur in an intrarotor and/or interrotor manner. For conventional aircraft, BVI noise can occur for forward/level flights and can be dominant in descending flight. For helicopter main rotors, when examining measured data, BVI noise is often treated as unsteady periodic noise through synchronous time averaging of the data across multiple revolutions. However, in prediction methods, BVI is often treated as periodic loading noise, as are other deterministic loading noise sources.

For electrified vehicles, the electric motor noise can be predicted with commercial multi-physics codes when all operational and design parameters of the motor are known. Lower-fidelity prediction approaches, such as those for system-type studies, have been explored and focused on the acoustic radiation from motor shell vibrations (either the rotor or stator, depending on the motor type). A three-element model is typically used where an electromagnetic forcing function is coupled with a motor shell vibration model, and the resultant shell vibrations are used for far-field acoustic radiation predictions [48-53]. Shell vibrations may be described by a simplified plate model [54] or by a parameterized model derived from finite element simulations [55].

### Nondeterministic (Broadband) Sources

There are generally both low- and high-fidelity methods for computing rotor/propeller broadband noise. For high-fidelity methods, all broadband noise sources can be predicted using subsets of the FWH equation (e.g., F1A) if the associated turbulent flow physics are resolved by the aerodynamic solver, because the resolved turbulence on the surface will behave as an unsteady loading component in the acoustic prediction. Other high-fidelity broadband noise prediction methods exist where the acoustic field can be directly computed during the aerodynamic calculation if a compressible solver of sufficient fidelity is used (i.e., scale-resolving simulations). These other high-fidelity methods are outside the scope of this document and are commonly referred to as the field of computational aeroacoustics.

Typically, large-scale turbulent structures, like those associated with wake dynamics, can be adequately resolved using hybrid Reynolds-Averaged Navier-Stokes (RANS)/large eddy simulation (LES) solvers. Fine-scale structures, such as those in the turbulent boundary layers associated with blade self noise, cannot be predicted using hybrid RANS/LES solvers. Wall-modeled LES (with some form of boundary layer tripping) or wall-resolved LES can be used to resolve turbulent boundary layers at great computational cost. In lieu of using these higher-fidelity flow solvers, low-fidelity acoustic prediction methods that do not require high-resolution boundary layer computations are often used to predict self noise. Amiet's trailing-edge noise theory [56,57], devised in the late 1970s, is used routinely to account for one of the five sources of blade self noise (as defined by Brooks, Pope, and Marcolini [58]), namely, turbulent boundary-layer trailing-edge noise. The calculation requires the spanwise correlation length and wall pressure spectrum (WPS) at the trailing edge of the blade. Corcos [59] is typically used for the spanwise correlation length. The WPS can be obtained from experimental data, simulation data from a suitable high-resolution scale-resolving simulation, or data modeled via physics-based approaches [60] or empirical approaches [61-65]. More recently, a modified Amiet's method was successfully used to model the vortices shed by blunt trailing edges by formulating the analytical method to consider a reversed Sears' problem [66]. An alternative semiempirical model based on NACA 0012 airfoil section data and acoustic measurements was devised in the late 1980s by Brooks, Pope, and Marcolini (the BPM method [58]). The BPM method models all five of the blade's self-noise sources: turbulent boundary-layer trailing-edge (TBLTE) noise, laminar boundary-layer vortex shedding (LBLVS) noise, bluntness vortex shedding (BVS) noise, tip-vortex formation noise, and separation/stall noise. Model deficiencies have been identified [67] for the prediction of LBLVS noise and BVS noise. BPM prediction requires information related to the boundary layer, section velocities, and section angles of attack along the span of a rotor blade. BPM currently lacks generality with respect to items such as multiple rotors and general cambered airfoil shapes.

To bridge the gap between the high level of empiricism associated with Amiet- and BPM-based low-fidelity methods and the prohibitively high computational cost associated with high-fidelity scale resolving methods (e.g., LES), one may consider stochastic methods to synthesize broadband noise sources based on input from a preceding RANS simulation. Good examples for these include the Stochastic Noise Generation and Radiation (SNGR) [68,69] and the fast Random Particle Mesh (fRPM) [70] methods, both of which stochastically synthesize turbulent velocity fluctuations based on the turbulence kinetic energy and dissipation rates from RANS. The broadband acoustic sources of complex geometries at high Reynolds numbers can be computed and propagated at a computational cost that is orders of magnitude lower than that of scale-resolving simulations.

BWI noise generally occurs as the result of turbulence associated with a tip vortex or wake structure interacting with a blade. Because this source is associated with turbulence, it is nondeterministic. Currently, there are only two low-fidelity approaches to predict this noise source: the method of Glegg [71] and the semiempirical method of Brooks and Burley [72]. Thus far, Glegg's method has not been validated for rotor geometries relevant to UAM vehicles and has not been used for the hover operating condition.

For TIN, the ingested turbulence can be free-field turbulence or that generated by urban canyons or bluff-body wakes behind buildings. This noise source can be predicted using Amiet's method [73,74], which, in addition to a noise model, includes an empirical method for the calculation of atmospheric turbulence at altitude [75]. The combination of two empirical models calls into question the applicability and validity of both, and TIN prediction using Amiet's method still needs to be validated for UAM propulsors.

Progress in models that can predict nondeterministic noise has partially satisfied recommendation SG1-2020-R1 and progress in coupling deterministic and nondeterministic prediction methods to design platforms has partially satisfied recommendation SG1-2020-R6.

### 2.2.1.2 Installed Sources

#### Aerodynamic Effects

BWI involves the turbulence field associated with, and outside the potential core of, the rotor-wake system. Turbulence interacts with the blade surface, thus creating unsteady loading that generates acoustic (dipole) radiation. Empirical modeling is currently the standard; however, this modeling is infrequent due to the lack of model generality and of experimental data to generalize the models. There is experimental evidence of interaction between rotors that affects broadband noise, and this is not currently modeled in most methods. The current interpretation is that the rotors are close enough that there is a strong wake-induced influence of one rotor on another that changes the broadband noise from each. With the anticipated multirotor configurations, with many rotors in proximity, this BWI effect will be more dominant than in conventional rotorcraft.

Several aerodynamic effects can also result from the installation of a rotating propulsion source near an airframe. These include, but are not limited to:

- unsteady loading on a blade in a wake deficit region, e.g., a pusher configuration.
- steady potential flow around the airframe, e.g., a propeller near the leading edge of the wing.
- recirculation of downwash, e.g., fountain flow.
- unsteady loading on the airframe, e.g., a horizontal strut near lifting rotors in a Lift + Cruise configuration.
- ducts in edgewise flight in which separated flow is ingested by the rotor, creating a source of unsteady aperiodic loading noise.

The above aerodynamic interactions affect tonal and broadband noise generation. The accuracy of the associated noise predictions is highly dependent on the turbulence modeling used by the flow solver. Consequently, the computational burden is high, making noise generation predictions difficult to address in general.

**Acoustics Effects**

Because the acoustics considered here are likely linear, the effects of all sources may be summed at the observer independently. However, the effects of the vehicle body and nearby reflective surfaces, such as those in urban canyons, on the propagation are not accounted for when using the integral-based acoustic analogy methods such as F1A, as the sound is propagated to the observer as if no other bodies are present. Scattering methods are used to account for the effects of reflections and shielding from bodies. These methods compute an additional acoustic field, with sources that account for the effects of reflection and shielding. This 'scattered field' is added to the incident source field to obtain a total acoustic field that satisfies the acoustic boundary condition on the scattering surface.

In the context of applying to UAM vehicle noise, several scattering methods have been developed to date. By approximating acoustic waves as particles that propagate along rays, geometric acoustics methods in the frequency domain [76] have been shown to be computationally efficient for broadband noise but are only accurate and formally valid in the high-frequency limit. They have also only been developed to propagate frame-fixed sources. Likewise, frequency-domain boundary element methods [77] solve the Helmholtz equation for a frame-fixed source distribution but are accurate at all grid-resolved frequencies. The drawback of these frequency-domain methods is that the computational complexity increases rapidly, limiting attainable frequencies, and they require separate computations at each frequency of interest. Time-domain boundary element methods [78-81] (TDBEM) solve the acoustic wave equation, allowing efficient simulation of transient sources, including aperiodic forcing from arbitrarily moving or rotating source distributions – a key advantage over frame-fixed frequency-domain methods. Another advantage of TDBEM is that the scattering solution at all broadband frequencies is resolved in a single computation, avoiding repeated assembly and inversion of large linear systems typically encountered in frequency-domain methods, which are computationally expensive for large-scale problems. This can offset the higher computational cost of TDBEM, especially if capturing the complex scattered fields at low- to mid-frequencies is of interest and more naturally couples with the predominantly time-domain computational fluid dynamics (CFD) solvers used to resolve noise sources.

Scattering methods are not routinely used for conventional rotorcraft because the fuselage has a limited scattering effect on the main rotor noise. However, it has been shown by Lee et al. [82] that scattering is significant for tail rotor noise even at the blade pass frequency (BPF) and at lower harmonics due to its higher RPM and position relative to the fuselage. For UAM vehicles employing tightly integrated multirotor-airframe designs, scattering may be also significant, as the vehicle configuration may place the scattering body in such a position with respect to the acoustic source as to increase the scattering effect (e.g., in the tip path plane). In addition, the wavelengths of sound are on the order of the characteristic lengths of the body and wing, further increasing the impact of the scattered field (and the numerical complexity of the associated computation). However, it must also be noted that in the complex case of installed rotors, the Helmholtz number alone is not sufficient to determine the acoustic compactness of a scattering body – the spatial structure of the rotor acoustic nearfield must also be considered. In the propeller-wing scattering work of Groom et al. [81], it was shown that when the wing is placed in the acoustic nearfield of the rotor, the rotor diameter has a strong impact on the scattering effect of the wing, leading to a significant scattered contribution even though the far-field acoustic wavelength is much larger than the wing chord.

Progress in both aerodynamic and acoustic effects of multi-propeller systems is beginning to address recommendations SG1-2020-R2 and SG1-2020-R3.

### 2.2.2 Sound Propagation Tools

The calculation of sound at the observer follows a source-path-receiver paradigm. Sound is typically defined on a hemisphere then propagated to the observer. For a given vehicle configuration, flight profile, and flight condition, the trimmed state of the vehicle is first determined. Achieving a prescribed steady state flight condition requires that the mean forces and moments acting on the vehicle sum to zero. When this state is achieved, the vehicle is said to be "trimmed." In the trimmed condition, the control surface configuration of the vehicle corresponds to the desired flight condition. In comparison to conventional rotorcraft, UAM vehicles have the potential to have many more redundant controls and, therefore, the same trimmed vehicle state can be achieved by various combinations of control settings. Because there are potentially multiple ways to achieve the same trimmed flight condition, there are potentially multiple representations of the source noise for a given flight condition.

The source noise hemispheres can be constructed with results from computations, flight data, model-scale data, or a combination thereof. A compact source is often assumed, and the observers are typically stationary. Two approaches for sound propagation are commonly adopted: a time-domain approach within a source-dominant simulation, and a frequency-domain approach within an observer-dominant simulation. The two approaches result in comparable noise metrics at the observer(s). Some sound quality metric calculations require acoustic pressure time histories to be generated after propagation, even if using a frequency-domain propagation approach. Propagation tools must account for at least three effects: spreading loss, time delay, and atmospheric absorption. Additionally, ground plane reflections need to be considered for observers above the ground plane. For very low-flying vehicles, more sophisticated ground plane reflection models accounting for spherical waves (versus plane waves) are required. Some researchers have begun to integrate UAM vehicle noise prediction with urban sound propagation [83-86].

System noise prediction tools, such as the NASA second-generation Aircraft Noise Prediction Program (ANOPP2) [87], are often used to support research and design. They typically integrate all elements of the source-path-observer paradigm, including source noise definition (including installation effects), propagation, and noise-certification metric calculations at a set of prescribed observer points for a specified flight trajectory. Tonal and broadband noise are typically computed on hemispheres for defined aircraft conditions. These source hemispheres are passed to a sound propagation tool, which computes the sound at the far-field observer (ground) locations throughout the flight trajectory. The propagated spectra are used to compute noise metrics used for certification such as effective perceived noise level (EPNL) or the A-weighted sound exposure level ($L_{AE}$, also SEL). They may also be used to generate metrics for use in community noise assessments when empirically derived data are unavailable. See Section 4 for a detailed discussion of community noise and auralization.

### 2.2.3 Facility Testing

Facility testing provides a controlled environment that is typically not available in outdoor ground and flight testing. Investigations often focus on components or subscale models. The results complement and improve aeroacoustic tool development. The identification of relevant configurations and physical quantities to measure are key parameters to consider. The configurations need to capture relevant features of the full-scale vehicles and acoustic, flow field, and performance measurements often need to be combined to understand sound source mechanisms and support modeling and computational efforts.

#### 2.2.3.1 Model-Scale Testing

Facility testing at a reduced scale offers measurement opportunities that might not be available at full scale. However, model-scale testing can pose challenges in terms of reproducing the full-scale physics of UAM vehicles. Some phenomena can be captured in these subscale tests with an adequately designed experiment while other phenomena are known to be impacted by scale in such a manner as to render the model-scale results as useful only in terms of providing trends.

Ensuring geometric features such as the rotor and airframe sizes, relative to the BPF-acoustic wavelengths, and the blade count in the model-scale experiments match those for the full-scale vehicle will increase the likelihood that acoustic scattering effects are replicated in the scale-model tests. If, in addition to matching relevant geometric features, similar disk loading is maintained, rotor-airframe interaction noise will likely be adequately reproduced in subscale testing as long as the interaction noise is dominated by the potential-field interactions.

Turbulence ingestion noise will be impacted by the temporal and spatial scales of the turbulence. While it may not be possible to explore the full range of relevant scales for a UAM vehicle in a model-scale test, it is possible to use the results for the scales that can be created in the experiments to validate computational tools, which can then be used to predict full-scale behavior. For turbulence ingestion investigations, measurements need to fully characterize the incident turbulence, including turbulence intensity, correlation lengths, and velocity spectra.

Model-scale propellers and rotors will exhibit low-Reynolds number effects that will be difficult to account for when relating to full-scale equivalents. However, relative trends in noise (such as with rotor collective and tip speeds) are similar to the full-scale platforms. Additionally, it is anticipated that relative changes in noise and performance of model-scale test articles will trend with their full-scale counterparts in studies focusing on transition and descent. However, certain flow-field features, such as tip-vortex core shape, and resulting interaction noise mechanisms, such as BVI, will likely exhibit some differences from their full-scale counterparts.

Model-scale testing will prove challenging for rotor-wake interaction noise, which is highly viscous in nature. Therefore, low-Reynolds number physics will likely yield rotor-wake features, namely tip vortices, that will result in interactional aerodynamics and noise that might not represent well the features of the full-scale counterpart. Additionally, blade deflections of model-scale rotor blades will not necessarily represent well their full-scale counterparts unless the blades have structurally scaled properties [88]. If full-scale predictions are to be made from model-scale data, it will be necessary to quantify the impact of the differences in the blade deflections for the model-scale and full-scale rotors on the resulting acoustic radiation. As such, diagnostics aimed at quantifying blade deflections should be incorporated in model-scale tests.

#### 2.2.3.2 Full-Scale Facility Testing

Testing at full scale presents a multitude of measurement challenges from both aerodynamic and acoustic standpoints. For a single propulsor (e.g., a propeller or rotor), the challenges include (1) propulsor slipstream influences on facility freestream uniformity, (2) very low-acoustic frequency measurement constraints of the facility, and (3) unwanted aerodynamic interactions with the interior structure of the facility (i.e., proximity of a rotor blade to the floor, walls, or shear layer of the facility). A full-scale propulsor in a simulated hover condition could have a high disk loading resulting in a slipstream that expands prominently both in the upstream (ahead of the rotor) and lateral (radially outward from propulsor hub) directions. The flow into the propulsor will, therefore, not be uniform. Additionally, a full-scale propulsor will have very low tonal, and possibly broadband, frequency content. The low-frequency acoustic characteristics of the facility are determined, in part, by the type(s) of acoustic treatment used in the facility, and this treatment may not be sufficient for measurements in the frequency range of interest (i.e., a blade passage frequency of 75 Hz). Particular attention should be paid to the cut-off frequency (anechoic limit) of the test section. When considering unwanted aerodynamic interactions, it has been commonly deemed acceptable for a wind tunnel model to exhibit a frontal area of 10% or less of the wind tunnel test section area. However, a propulsor with high disk loading could result in a slipstream that is in close proximity to the test-section shear layers, boundary layers, or solid surfaces. Upstream flow surveys should be performed to ensure flow uniformity across the range of desired test conditions.

#### 2.2.3.3 Measurement Practices

Acoustic measurements typically involve multiple microphones to capture directivity or large channel-count phased arrays that provide noise-source localization through beamforming and address signal-to-noise ratio deficiencies. De-rotational algorithms allow for localization of stochastic/broadband noise sources on rotor blades while also removing the rotational/deterministic components of rotor noise [89]. Sensor frequency ranges must include those frequencies of interest for the vehicle while accounting for the acoustic wavelength scales with the characteristic length scale. As such, a sensor used for a half-scale model will need an upper frequency limit that is twice the maximum frequency of interest for the vehicle when the atmospheric conditions for the model and full scale are similar.

Aerodynamic measurements in addition to rotor performance measurements (e.g., thrust, torque, side forces and moments) need to accompany acoustic measurements. Flow-field measurements of the rotor inflow, slipstream boundary, vortex trajectories with provisions for wander, rotor disk wakes, and rotor-blade wakes are important for aerodynamic solver validations. On-airframe pressure measurements provide incident pressure data to inform scattering prediction efforts. On-blade measurements such as infrared thermography, pressure sensitive paint, and wall pressure spectra are useful for self noise prediction validation efforts. Frequency response is critical for evaluation of sources such as turbulence ingestion noise and blade self noise and may require integrated high-bandwidth instrumentation such as hotwires or surface pressure microphones on blades. Blade deflections via digital image correlation or phase-locked high spatial resolution stereo camera systems are a potentially very important measurement to properly address deviations in performance and acoustics of propeller/rotor blades across different scales due to blade-shape deviations associated with different materials.

#### 2.2.3.4 Datasets for Tool Validation

Experimental datasets with configurations relevant to UAM aircraft are available through NASA for tool validation. The configurations used in the experiments include an optimized UAM proprotor [90], a hovering ideally twisted rotor [91,92], a scaled notional eVTOL rotor [93], a vertical lift proprotor [94], and a multirotor [95]. These datasets predominantly focus on isolated rotor configurations and include a rotor or rotors in hover, transition, axial forward flight, and edgewise forward flight. The experimental data are limited to rotor aerodynamic loads and acoustics.

### 2.2.4 Noise Reduction Technologies

Rotor noise mitigation techniques have been explored using both active and passive means. Reduction in high-frequency BVI noise has been achieved with active blade pitch control and higher harmonic control, as demonstrated in tests with tilt-rotor configurations [96,97]. Noise control through constructive and destructive interference of the sound waves generated by neighboring rotors has demonstrated significant reductions in tonal noise for multirotor platforms operating in both side-by-side configurations [98-100] and for stacked co-rotating rotors [101].

Other methods of source noise reduction can be incorporated through the design of the propulsors themselves. For example, the incorporation of an anhedral rotor tip design yields an increase in the vortex miss distance from the blades and thus reduces perpendicular BVI events. This, in turn, has been shown to yield a performance benefit and can potentially reduce resulting BWI noise generation [102,103]. While investigations into the acoustic benefits of blade-tip anhedral are still in their infancy, it is worth noting that some current UAM vehicle developers are implementing this design feature into their blades. The use of low-fidelity, gradient-based blade-design optimization has shown that a further reduction in source tonal and broadband noise can be achieved by a combination of reducing tip speed and optimizing blade pitch and chord length to maintain performance [90,104]. Another strategy involves using uneven rotor blade spacing, which can help reduce tonal noise and reduce perceived annoyance by spreading concentrated sound energy across a broader frequency spectrum [105]. Also, stacked or multi-blade co-rotating propeller configurations, referred to as “stacked lift props,” can contribute to noise reduction by lowering the blade loading compared to two-bladed lift propellers and by adjusting the azimuthal phase offset and vertical spacing between the upper and lower props [106,107].

## 2.3 Gaps

### 2.3.1 Prediction Tools

Gaps in prediction capability mirror the noise source and propagation paradigm currently employed to predict UAM vehicle noise. Gaps in experimental validation data are also addressed.

#### 2.3.1.1 Source Noise

**Isolated Sources**

The study of isolated sources continues to be the primary focus of UAM vehicle noise research. One model that needs further improvement is broadband self noise. Methods to estimate the correlation length scale and WPS associated with blade self noise need to be developed. Existing models are based on the physics of an attached turbulent boundary layer and, therefore, cannot be used for sources such as laminar boundary-layer vortex shedding and separation/stall noise. Additionally, the low-fidelity broadband noise modeling based on BPM needs to be improved for UAM propellers. The BPM model was developed based on data from the NACA0012 airfoil shape, so models for the individual noise sources need to incorporate improved empirically based noise-prediction models and boundary layer estimates that rely on datasets from more UAM-relevant airfoil geometries.

Both BWI and TIN, two similar noise-source mechanisms, require additional modeling improvements. BWI noise prediction, using an aerodynamic solver of high-enough fidelity (i.e., hybrid RANS/LES or higher fidelity) coupled with the subsets of the FWH equation (e.g., F1A), requires additional investigation. Recent work by Thurman et al. [92] utilized a hybrid RANS/LES solver coupled with an F1A code and showed both a leading edge and trailing edge component associated with BWI noise for a small 4-bladed rotor in hover. In addition, TIN noise based on Amiet's empirical method requires validation of both the turbulence and the acoustic models. An experimental effort is required to generate the validation database (discussed in the following subsection) to validate and modify Amiet's method for UAM application.

Similar to rotorcraft, descent is expected to be the flight condition where noise is of particular importance, as the vehicle will be operating near communities. There is a need for aerodynamic and aeroacoustic-capable methods that can approximate the descent conditions and provide an accurate assessment of radiated noise.

For electrified vehicles, validation of low-fidelity electric motor noise predictions for motor configurations relevant to UAM vehicles is needed, particularly for high-aspect ratio motors, where complex vibration-mode shapes may not be well represented by simple cylindrical mode shapes [55]. While cabin noise is beyond the scope of this paper, it should be noted that, if motor noise is determined to be of significance to the cabin environment, the impact of the motor installation on the radiated noise requires further investigation.

Recommendations to address the gaps in the development and validation of UAM noise sources are summarized in recommendations SG1-2020-R1, SG1-2020-R2, SG1-2020-R3, SG1-2020-R6, and SG1-2025-R1.

**Installed Sources**

While the current focus of UAM noise-prediction methods is on isolated sources, accurate noise assessments for these vehicles will require the focus to shift to installed source-noise models due to their complex aerodynamic environment. The first gap in installed source noise models is understanding when aperiodic versus quasiperiodic methods are required. For helicopters, that transition occurs when the time scale of the maneuver approaches the time scale of the rotor revolution. Because UAM vehicles operate with rotors at different revolution rates, it remains unclear when aperiodic versus quasiperiodic methods are necessary. While most time-domain acoustic solvers can perform aperiodic predictions, these solvers have not been routinely used because periodic assumptions have proven valuable for rotorcraft applications and, therefore, are a good starting point for UAM applications. However, full-vehicle noise prediction, where there is more than one rotor revolution rate, may require aperiodic methods. Furthermore, it is also worth noting that periodic solutions will be inherently devoid of stochastic noise sources, such as those related to turbulence. It is anticipated that UAM applications will have a stronger presence of these types of noise sources, which further reinforces the potential need for aperiodic solutions.

Acoustic scattering has been shown to significantly alter radiated noise both in terms of its intensity and directivity. UAM vehicles that have propellers near lifting surfaces, such as wings, can also have a fuselage with a characteristic length that is on the order of the acoustic wavelength of the blade passage frequency. Of all the acoustic scattering methods currently available to the UAM community, none, except for the space-time Galerkin TDBEM code developed by Groom et al. [81], are capable of handling transient, rotating, and broadband noise sources with arbitrarily moving sources and scattering geometries often encountered in UAM vehicles. Geometric acoustic methods based on high-frequency assumptions are not applicable in the frequency ranges where blade passage frequency tones occur for these vehicles. As such, capturing the radiated noise from the multiple acoustic sources of UAM vehicles may require a hybrid approach. Such a hybrid method could be one in which a time-domain boundary element method is applied at lower frequencies, and a geometric acoustics method is applied at higher frequencies.

Recommendations to address the gaps predicting both aerodynamic and acoustic effects of installed multi-propeller systems are summarized in recommendations SG1-2020-R2, SG1-2020-R3, and SG1-2025-R1.

### 2.3.2 Experiments

There are currently very few experimental datasets available that document the combined aerodynamics and acoustics of UAM propulsors in LTO or transition flight conditions. However, there are test campaigns in the literature that have looked at propeller performance behaviors at high angles of incidence [94,108]. Findings from these studies have identified considerable deviation in propeller performance from analytical theory above a certain range of incidence angles, indicating a need for further investigation. Furthermore, these modes of flight are anticipated to be important for community noise due to the nonideal operating conditions of the vehicle propulsors where high blade angles of attack and wake interactions are expected.

It is often more cost effective and efficient to test subscale geometries in lieu of their full-scale counterparts; however, there are often nuances associated with subscale testing. Geometric and dynamic similarity between the subscale and full scale is required. Assuming geometric similarity, dynamic similarity is attained by matching tip Mach number and Reynolds number. Matching the tip Mach number is often trivial, but matching the Reynolds number is extremely difficult without test facility pressurization and/or the use of cryogenic gas. Without these specialized facilities, subscale proprotors typically have significantly lower Reynolds numbers than those for full-scale proprotor operating at the same tip Mach number. Low-Reynolds number effects such as laminar separation bubbles or early separation due to decreased skin friction may become prevalent and cause a disparity in the aerodynamics and acoustic sources between the two geometric scales. For this reason, boundary layer tripping of the subscale proprotor blades is often warranted; however, the effective boundary-trip type and size is highly dependent on the blade boundary layer itself and will differ for different operating conditions. It is still unknown if a subscale geometry with an adequately tripped boundary layer will suitably replicate the aerodynamic and acoustic characteristics of its full-scale counterpart.

Due to the potential for highly complex flow fields, high-fidelity aerodynamic solvers, such as CFD, may be computationally prohibitive for a large design space, i.e., for a large parametric study. Therefore, mid-fidelity analytical, semi-analytical, and/or estimation-based modeling methods are warranted but not yet fully developed. For example, there have been recent advancements in the application of artificial neural networks for the modeling of rotor-airframe interaction noise [109], but these have not yet been applied to UAM tool chains.

To date, the number of publicly available UAM vehicle and proprotor geometries is very small. Because of this, most subscale proprotor testing has focused on sUAS geometries rather than subscale versions of realistic and representative UAM geometries. Aside from the relative size difference between sUAS and UAM vehicles, the proprotor blade designs are different due to the differences in vehicle operating condition demands. Moreover, the aerodynamic flow field and acoustic sources may be dissimilar between a sUAS and UAM propulsor.

Electric motor noise has been shown to contribute to the acoustic signature of sUAS [110]. Evidence that electric motor noise is present in far-field acoustic radiation for UAM vehicles is limited [111] due to the lack of available full-scale vehicle data and the challenge in separating electric and rotor-related noise in measured spectra, as both occur at multiple shaft-order frequencies. Comparisons with isolated motor measurements are beneficial, but acoustic levels increase when the motor is loaded [52], and the motor-loading apparatus can result in extraneous noise sources unrelated to actual installation effects in the vehicle.

Recommendations to address the gaps in experimental activities for UAM noise prediction are summarized in recommendations SG1-2025-R1 and SG1-2025-R2.

## 2.4 Recommendations

Understanding the complex dynamics of UAM vehicle aeroacoustics requires the evolution of computational tools and experimental approaches. An assessment of the previous recommendations and introduction of new recommendations are provided below.

### 2.4.1 2020 Recommendations

Further development of validated noise prediction tools is required to support research and development of vehicles and their operations. Specifically:

SG1-2020-R1. System noise prediction tools, developed primarily for assessments of large commercial transports and used more recently for rotorcraft noise assessments, lack fully integrated source noise (including installation effects) prediction methods and advanced propagation tools required for UAM vehicle design and noise reduction technology development. It is recommended that system noise prediction tools be further developed for application to UAM vehicles and made available to the research and industrial communities. **[Progress Made]**

SG1-2020-R2. The introduction of new vehicle configurations employing multiple rotors with potentially different rotational speeds not only generates aperiodic noise but allows the same vehicle to execute a particular flight condition in more than one manner due to redundant controls. In such cases, current methods to trim the vehicle (including installation effects) and subsequently perform acoustic analyses are inadequate. It is recommended that research be performed to develop conventions on how to handle control redundancies to obtain preferred low-noise trim conditions and to further develop the acoustic tools to handle aperiodic sources. **[Progress Made]**

SG1-2020-R3. Many existing source noise models, including those currently under development, have not been fully validated at UAM scales. Further, there is a need to understand the relative amplitudes of dominant noise sources for archetypal vehicle configurations across the full operational range. It is recommended that prediction models for the highest amplitude noise sources be validated with experimental data for isolated and installed configurations, and that flight test data be acquired to better understand variations under realistic operating conditions, particularly unsteady conditions (e.g., maneuvers and transition). Documentation of some or all of these data should be made publicly available as a comparison data set, as has been done for efforts such as the American Institute of Aeronautics and Astronautics (AIAA) Benchmark Problems for Airframe Noise Computations (BANC) workshops [112]. **[Progress Made]**

SG1-2020-R5. There are a number of potential noise mitigation technologies which appear well suited for application to UAM vehicles; however, many of these are based on laboratory demonstrations and have yet to be matured and demonstrated in flight. It is recommended that a dedicated technology maturation effort be performed on the most promising technologies and that opportunities be sought to evaluate their efficacy in flight. **[Open]**

SG1-2020-R6. Noise prediction tools used for research and noise reduction technology development have limited application early in the design process because of both computational effort and the level of detailed information needed. Sensitivities should be developed and implemented throughout the design tool chain. It is recommended that surrogate or other reduced order model methods be developed so that designers can quickly determine the effects of design changes on noise early in the design process, and that sensitivities be fully implemented to enable optimization of low-noise vehicle designs and operations. **[Progress Made]**

SG1-2020-R8. Noise abatement procedures for piloted and autonomous UAM operations may be difficult to generalize due to the wide variety of UAM vehicle concepts. In the absence of generalized guidance, it is recommended that manufacturers work with appropriate organizations, e.g., the Fly Neighborly / Environmental Working Group, to develop low-noise guidance for piloted operations and automated low-noise procedures for autonomous operations that are specific to their products. **[Open]**

Note that recommendations SG1-2020-R4 and SG1-2020-R7 have been realigned to Sections 4.4.1 and 5.4.1, respectively.

### 2.4.2 2025 Recommendations

It is recommended that:

SG1-2025-R1. A common research platform (i.e., vehicle configuration and/or canonical geometry) be established. From here, combined experimental and computational investigations can be conducted on the pertinent aeroacoustic phenomena. For example, if a multi-tiltrotor platform were identified, different aerodynamic and/or acoustic investigations could be performed related (but not limited) to:

- Rotor-rotor interactions associated with LTO and descent/approach conditions
- Acoustic scattering
- Prop-airframe interaction aerodynamics and acoustics
- Modeling of atmospheric impacts (i.e., turbulence ingestion) on performance and noise
- Full vehicle-level aeroacoustic predictions

SG1-2025-R2. In addition to measurements of radiated noise and integrated performance, experimental studies carefully characterize the unsteady aerodynamic interactions on (e.g., unsteady surface pressure) and around (e.g., inflow, wakes, etc.) rotors when possible. This is critical for assessment of contributing noise sources, validation of computational and analytical tools, and comparison with the findings of others.

Note: Recommendations SG1-2025-R1 – SG1-2025-R2 align with recommendation 4.3 and 7.7 in the AAM National Strategy [8].

# 3 Ground and Flight Testing

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## 3.1 Introduction

Ground and flight testing play an essential role in characterizing acoustic radiation from aircraft. The data can be used to improve our understanding of sound-generation mechanisms, determine the effects of their sound generation on the communities in which they operate, plan operations or trajectories which minimize the sound, or evaluate noise reduction strategies and their implementation. With a new age in Advanced Air Mobility on the horizon, of which UAM is a part, it is conceivable that many of the existing methods and techniques developed for testing modern fixed- and rotary-wing aircraft may need to be adapted for application to UAM vehicles.

In this subsection, the historical motivation for acoustic testing will be introduced, followed by a high-level assessment of the practices already common across the aeronautics industry. Challenges and potential gaps in applying these practices to emerging UAM platforms will be identified, and considerations for future measurement standards will be discussed. The topics discussed here align with recommendation 4.3 of the AAM National Strategy [8].

### 3.1.1 Why conduct acoustic testing?

There are many reasons a manufacturer, the government, or a research organization might initiate an acoustic test campaign; however, they can be broadly categorized into three main groups: certification, research, and community response/assessment. While similarities and overlap of testing requirements may exist between categories, the processes for each may require unique and diverse combinations of equipment, flight procedures, and analysis methods.

Certification testing is used as the primary regulatory method to assess and control the sound produced by aircraft. Noise-certification flight-testing procedures that are in use today were largely developed to quantify the sound produced by individual aircraft in the vicinity of commercial airports. The procedures are intended to provide a standardized basis to compare the sound generated by various aircraft of the same type and/or vehicles capable of performing equivalent missions. Data are acquired for the full-size, production-representative vehicle conducting a limited set of tightly controlled flight procedures, representative of real-world operating practices. The data are used to compute specific noise metrics that act as a proxy for effects on communities. The tightly bounded scope of the procedures is intended to minimize the cost burden on manufacturers. A more detailed discussion on regulatory aspects related to certification flight testing is presented in Section 5.

Research-focused acoustic flight testing typically aims to gather larger quantities of data, using more instrumentation, with more involved processing techniques than those for certification. Testing is often employed during the development of new aircraft concepts, where data may be leveraged to develop new empirical or semiempirical models, or to validate existing models such that they can be confidently used to guide the design of the new vehicles. While model-scale testing in appropriate wind tunnels or anechoic facilities remains important, full-scale effects and complex interactions may only be captured from full-scale flight testing. Furthermore, when unanticipated or undesired sound sources and/or levels are identified during certification, testing requirements needed to diagnose and mitigate these issues are significantly more involved than those required for certification; hence, research style procedures must be employed. However, due to the cost of conducting these larger research endeavors, many aircraft never undergo this level of testing unless a failure to meet certification requirements is foreseen.

If flight-test data are to be used for community-related assessments, there may be different test requirements from those for research-focused and certification testing. These data may be used in models to assess community responses to flight operations or within lab studies aimed at correlating human responses to aircraft noise. Community noise surveys are an important step in the introduction of novel vehicle configurations, where exposure-response relationships may not exist or may require significant updating. A more detailed discussion of these methods is provided in Section 4.

Community and airport noise monitoring systems have played an important role in auditing the actual exposure from traditional aircraft and their data have sometimes been used to modify noise predictions at an airport. As later noted in Section 5.2.2.3, noise monitoring data should not be used to calibrate the noise model. The introduction of novel flight vehicles, such as UAM aircraft, may necessitate flight tests to validate the correct functioning and positioning of sensors for their expected operations. It should be noted that the signal-to-noise ratio of these community-embedded measurements may be significantly lower than current airport-adjacent noise monitors, suggesting advanced measurements or postprocessing techniques may be needed to extract meaningful information from the data.

## 3.2 Current Practice

For noise certification, the ICAO currently defines the standards and the measurement procedures for separate categories of traditional aircraft, which form the basis of national regulations developed by applicable regulatory authorities such as the FAA or the EASA. Though the minutiae of the noise certification procedures vary for different aircraft types, the general approach remains the same. An aircraft is flown in controlled flight conditions over one or more microphones. Acoustic data are acquired and specified noise metrics are computed once the data are corrected for environmental conditions and flight-path deviations. The computed metrics are compared to the noise limits for the particular category of aircraft and a determination of noise compliance is made. While no internationally consolidated noise certification standards currently exist for UAM aircraft, a summary of the existing noise certification standards and procedures that may be applicable to UAM aircraft is given in Table 1. Note that the term "Flyover" appearing in 14 CFR Part 36 [113] has been replaced with the equivalent term "Overflight" used in Annex 16 Vol 1 [7]. "Pole" mounted microphones are at 4 ft (1.2 m) above the ground and "Ground" indicates inverted microphones over a ground plate. The sideline microphones are offset to either side of the flight track by ±492 ft (150 m).

In the absence of internationally consolidated noise certification standards for UAM vehicles, the EASA has developed its own interim noise certification requirements for UAM aircraft, referred to as "vertical take-off and landing capable aircraft" (VCA) by the EASA. These initially took the form of separate Environmental Protection Technical Specifications (EPTS) for VTOL-capable aircraft powered by non-tilting [114] and tilting [115] rotors. More recently, these requirements have been consolidated into a single document within the Notice of Proposed Amendment (NPA) 2025-03 [116]. A summary of the NPA specifications is provided in Table 2. The "Pole" and "Ground" microphone definitions are the same as those for Table 1. The sideline microphone locations can be placed at the traditional lateral offset from the flight track of ±150 m. Smaller microphone offset distances are allowed if lower aircraft altitudes are required to meet signal-to-noise ratio restrictions as long as the elevation angles are equivalent to those obtained when using the traditional flight maneuvers and sideline microphone locations. The cruciform measurements have two microphones located on each of four arms of a cross and one microphone located at the hover origin.

Table 1: ICAO and FAA noise certification standards and procedures that may apply to future UAM aircraft.

| Annex 16 Chapter | Part 36 Appendix | Aircraft Type | Metric | Microphone Setup | Microphone Locations | Flight Procedure | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | Takeoff | Overflight | Approach |
| 8 | H | Helicopters | EPNL | Pole | 1 centered on flight track<br>2 sidelines | ✓ | ✓ | ✓ |
| 11 | J | Helicopters ≤ 3,175 kg max cert takeoff mass | $L_{AE}$ | Pole | 1 centered on flight track | | ✓ | |
| 10 | G | Propeller-driven airplanes ≤ 8,618 kg | $L_{Amax}$ | Ground | 1 centered on flight track | ✓ | | |
| 13 | K | Tiltrotors | EPNL | Pole | 1 centered on flight track<br>2 sidelines | ✓ | ✓ | ✓ |

Table 2: EASA NPA 2025-03 [116] requirements applicable to UAM vehicles.

| Derived From: | Aircraft Type | Metric | Microphone Setup | Microphone Locations | Flight Procedure | | | |
|---|---|---|---|---|---|---|---|---|
| Annex 16 Chapter | | | | | Takeoff | Overflight | Approach | Hover |
| 8 | Non-tilting | EPNL | Pole | 1 centered on flight track<br>2 sidelines | ✓ | ✓ | ✓ | |
| | | $L_{Aeq}$ | Ground | 1 centered below vehicle<br>2 per cruciform arm | | | | ✓ |
| 13 | Tilting | EPNL | Pole | 1 centered on flight track<br>2 sidelines | ✓ | ✓ | ✓ | |
| | | $L_{Aeq}$ | Ground | 1 centered below vehicle<br>2 per cruciform arm | | | | ✓ |

The specification for non-tilting powered vehicles in the NPA is derived from the existing certification standards for helicopters (Annex 16, Chapter 8); where certification is conducted with takeoff, overflight, and approach procedures. An additional hover test procedure is required, although no maximum noise limits are defined. The NPA specifications for tilting rotor VTOL aircraft are derived from existing standards for tiltrotors (Annex 16, Chapter 13). The procedures for takeoff, approach and hover are the same as those for non-tilting rotors, with the addition of maintaining nacelle angle for the takeoff condition. The overflight procedures include airplane and conversion modes. For the airplane mode, the nacelle angle is aligned with the longitudinal axis of the aircraft. For the conversion mode, the nacelle angle is maintained closest to the lowest nacelle angle certificated for zero airspeed. The latter mode will result in very different, and likely higher, acoustic levels than those for the airplane mode. However, it should be noted that sustained flight in the conversion mode may prove difficult or impossible for many vehicles without modifying their control laws, as this may not be a flight condition that falls within the standard operating procedures for the vehicle.

Research flight tests for both fixed-wing and rotorcraft often deploy large channel-count arrays typically with microphones that are flush-mounted or inverted on a ground board and distributed over thousands of square feet. Rotorcraft processing methods may include backpropagating data gathered from steady flyover conditions to map the sound to a hemisphere surrounding the vehicle. Acoustic source hemispheres, per flight condition, can then be used as a database for empirical or semiempirical source models and/or exposure modeling purposes [117]. Unsteady test conditions, e.g., maneuvers or any flyover involving acceleration, are often characterized through ground noise footprints or, more recently, with snapshot arrays in which a short time interval (~ 0.5 s) is used to compute spectra for all microphones as the aircraft passes over the array origin [118]. While depropagation techniques and noise hemispheres are used for fixed-wing aircraft, phased arrays with beamforming for source separation are also common. A comprehensive overview of methods associated with research-focused acoustic flight testing for UAM aircraft can be found in Ref. [119]. These methods commonly use large channel-count ground arrays with specific arrangements selected to meet the exact purpose of the test. In-flight measurements have also been conducted using either quiet chase aircraft [120], helicopter-mounted boom arrays [121], or even a hot air balloon [122].

As UAM vehicles are expected to operate in closer proximity to communities, at higher operational cadence than conventional aircraft, and while being more geographically dispersed throughout urban areas, the size of the potential impact area associated with their acoustic emissions may be substantially larger than that of traditional aircraft. Furthermore, a wider range of vehicle states is expected to contribute to community noise exposure, which must be accounted for when modeling UAM noise. Common methods for presenting acoustic flight test data for modeling purposes include acoustic hemispheres, used by simulation tools, e.g., the Advanced Acoustic Model [123], and Noise-Power-Distance (NPD) curves, used by integrated noise modeling tools, e.g., the FAA Aviation Environmental Design Tool (AEDT) [124]. Instructions for constructing vehicle-specific NPD data are detailed in the SAE AIR 1845A standard [125], the AEDT technical manual [124], and other references [126]. NPD data have also been generated from system acoustic analyses [127,128].

Acoustic flight-test measurements, whether for certification, research, or effects on communities, should employ best practices where applicable. The test site should have relatively flat terrain and be without any excessive sound-absorbing materials (e.g., dense foliage, tall grass) or large obstructing bodies (e.g., buildings). Ambient sound levels must be low, relative to those from the aircraft, and free of significant tonal content, particularly for propeller and rotary-wing aircraft. These recommendations may be relaxed when the test objective is to assess the impact of these features on the acoustic measurement. Allowable atmospheric conditions are specified in the standards presented in Tables 1-2, where slight variations exist between aircraft categories and test procedures. Sound pressure levels should be corrected for deviations in environmental conditions, with recommended procedures again outlined in the standards of Tables 1-2.

Aircraft position is determined by Global Navigation Satellite Systems (GNSS) using Single Point Positioning techniques (SPP) or, for higher-resolution research-type tests, Real-Time-Kinematic (RTK) or Post-Processed Kinematic (PPK) techniques. Microphone positions are typically determined using survey-type GNSS. Synchronization of the aircraft position, state, and acoustic measurements is commonly achieved using GNSS timestamps and common time signals. Importantly, proper record keeping detailing the measurement procedures, test conditions and post-processing steps should be retained with any data.

## 3.3 Gaps

With the advent of UAM vehicles, it is anticipated that existing measurement methodologies may need to be adapted or modified. This subsection details many challenges associated with the application of current techniques to UAM ground and flight acoustic testing.

### 3.3.1 Source Prioritization

Currently, many UAM aircraft configurations are under consideration. The noise-source prioritization for these aircraft may be different from that for traditional fixed- or rotary-wing aircraft. While traditional sources such as thickness noise, loading noise, and, in certain cases, BVI noise will be present for VTOL-type configurations, nontraditional rotorcraft sources such as those associated with distributed propulsion systems or transitional flight states are also expected. Noise sources from ducted rotors may also be relevant for some configurations. Airframe noise, fan noise, and possibly even jet noise will be present for configurations with wing-integrated ducted fans or turbofans. Additionally, sources associated with atmospheric turbulence interacting with rotating blades (often labeled turbulence ingestion noise) can be prominent, particularly in hover or for low flight speeds.

Propulsor-propulsor and multi-propulsor-airframe interactions will likely be of increased importance relative to conventional aircraft, especially for VTOL-type configurations, where operational tip speeds are expected to be lower than those of traditional rotorcraft. Multiple independent propulsors result in multiple shaft frequencies that impact structure-borne sound and direct acoustic radiation. When the rotational speeds of the multiple propulsors are nearly the same but not identical, beating can occur. Beating occurs by the summation of two sinusoids with slightly different frequencies and results in an amplitude modulation of the combined signal at a beat frequency equal to the difference between the two sinusoidal frequencies. However, when the frequency differences increase to roughly a few percent, coherence is reduced, and beating may no longer occur. Nondeterministic noise sources, e.g., propulsor-wake interactions, atmospheric effects, and turbulence ingestion, are not well understood and should be investigated with measurements.

For many aircraft and flight profiles, landing and takeoff noise (and their associated measurements) should be prioritized for two reasons. First, these phases of the mission are performed near the ground, and hence, to communities and the local population. These low-altitude events have the potential to introduce significant increases in community ambient-sound levels. In contrast, relative to takeoff and landing, the cruise segments of the mission are expected to generate lower acoustic levels due to increased separation from the community and possibly through the use of wing-borne flight. Secondly, many UAM aircraft configurations involve propulsor transition to/from VTOL to axial forward flight. Transition is an aerodynamically, and thus aeroacoustically, complex procedure that can shift the dominant sources from those for hover or cruise. Leveraging mid- or high-fidelity predictions would be useful in identifying flight test conditions with an increased likelihood of transition or interactional noise sources.

New recommendation SG2-2025-R1 addresses this gap.

### 3.3.2 Complex Operating Environment

The operating environment will involve nearby cityscape and vertiport structures unique to each location. Measurement standardization will be challenged by the large variation in vertiport size and configuration, including the vertiport height above ground. Urban canyons will have large variations in length scale, and geometrical features will result in reflections, reverberation, and diffraction, and may act as waveguides. Urban landscapes can also have complex meteorological properties, which can influence sound propagation and perception. Measurements within such environments are critical for developing and validating multipath propagation tools and for noise predictions for these environments (see Section 2.2.2) but can have large uncertainty bands if not handled with substantial care. Defining canonical urban geometries and testing in those environments, with simple sources under controlled or well-characterized meteorological conditions, may expedite development.

During all segments of the flight envelope, large variations in the background sound levels and characteristics may occur, and these changes must be quantified and considered in the development of measurement procedures and prioritization of flight test conditions. Standard procedures for characterization of community background soundscapes may be helpful in this regard [129,130], as identified in recommendation SG3-2020-R2 and discussed in Section 4.2.1.1.

New recommendations SG2-2025-R1 and SG2-2025-R4 address this gap.

### 3.3.3 Variation in Operating Condition

Significant variations in operational configurations and environment of UAM aircraft occur throughout their flight envelope for some vehicles. These variations introduce a host of challenges when developing flight testing procedures. During takeoff and approach, these vehicles alter configuration when transitioning to, and from, forward flight. This transition can involve a reconfiguration of thrusters, changes in wing/propulsor loading, variation in vehicle orientation, and more. Transition may prove the most challenging flight regime to measure due to the time-dependent nature of the radiated sound, but it may be important to capture it as the source priorities are not well understood, and the acoustic radiation might be significant. An additional challenge to defining a testing procedure is that the transition is influenced by the onboard flight control algorithms that may have operational latitude to achieve a given mission and may be subject to change during vehicle development and throughout the life of the vehicle.

In addition to configuration changes, UAM aircraft have complex operational states due to their high number of degrees of freedom (relative to conventional aircraft). Additionally, these increased degrees of freedom will likely result in far greater trim-state flexibility than conventional aircraft. These vehicles can have control schemes that use several propulsor inputs, each with individual rotation rates and blade pitches, which might lead to variable trim states that depend on multiple factors, such as the current environmental conditions, the battery charge, and the prior vehicle state. It may also be possible for a vehicle control scheme to be modified to reduce radiated sound during segments of the mission, but this adjustment may also slightly penalize energy efficiency. All these factors complicate the development of standardized flight-testing procedures.

The time-dependent nature of sound generation during transition poses unique measurement challenges, and capturing acoustic signatures during this segment of flight will be difficult without large ground microphone arrays or simplifying assumptions about the transition procedure. A snapshot array is one concept that can meet this need. It may be necessary to deploy multiple snapshot arrays or conduct multiple maneuvers over a single array to capture the acoustic features for the entire transition.

Acoustic radiation for hover can also be highly variable for UAM vehicles. To accurately represent the acoustic radiation for this maneuver, many measurements may be necessary. If turbulence ingestion is the dominant contributor to the measured acoustic variability, it may be more appealing to characterize hover as a range of levels, particularly if those ranges can be related to atmospheric characteristics. An alternative approach is to take many measurements over the full range of relevant atmospheric conditions to obtain a representative average. Because many of these vehicles were not designed for extended hover, repeated acquisitions are challenging, likely forcing a tradeoff between the number of measurements and test practicality. Where possible, acoustic data should be taken in the far field to enable simple scaling laws to be applied. Limited data are available for the determination of the near field/far field transition for specific UAM aircraft configurations [111], but the dependence on overall vehicle characteristic needs to be better understood. If these measurements are to be used for model development, characterizing the conditions leading to the variability might be difficult but will likely be necessary. Both numerical [131] and experimental [132,133] studies are being conducted to understand the real-world turbulence statistics near UAM operating environments; however, further work is needed.

For hybrid-electric vehicles, ground-idle noise may be important, as these vehicles may keep their engines running while on the ground prior to, or between, missions. Because vertiports are expected to be close to populated areas, the acoustic radiation associated with idle may contribute to the overall noise footprint of the vertiport. The sound generated by idling may be important for vertiport planners, thus requiring measurement and quantification of this sound source.

This gap relates to the open 2020 recommendation SG2-2020-R4. Additionally, new recommendations SG2-2025-R1 and SG2-2025-R3 address this gap.

### 3.3.4 Expanded Directivity Requirements

For conventional aircraft, most acoustic testing is conducted with ground-based (not to be confused with ground-level) microphone arrays, although microphones mounted on towers [134] or hot air balloons [122] have been used in a few tests to augment ground arrays and increase the range of angles captured in the measurement domain. These ground arrays have merit for existing helicopters and fixed-wing aircraft operating in and around airports. UAM aircraft will likely operate in urban environments and, therefore, may require supplementary measurements at positions near, and above, the aircraft horizon to assess their acoustic radiation as they approach and depart from highly populated urban canyons. Previously implemented methods using microphones suspended from towers and hot air balloons, or mounted on gliders, are possible candidates to achieve these above-the-horizon measurements. The expansion in use of sUAS for airborne sensing tasks (including acoustic localization [135]) makes their use a favorable candidate.

Unfortunately, elevated acoustic measurements incur unavoidable ground reflections, which can corrupt both signal amplitude and resulting spectra. The tonality of UAM vehicle noise may also produce relatively high partial coherence of the direct and reflected signal, further exacerbating this issue. Therefore, novel measurement or processing techniques are likely needed beyond current practice for quality elevated measurements to be performed. If a full acoustic sphere is desired but above-the-horizon flight-test data of sufficient quality are unavailable, acoustic hemispheres below the aircraft measured by ground-based systems could be supplemented with numerical simulations.

This gap relates to the open 2020 recommendation SG2-2020-R4. Additionally, new recommendation SG2-2025-R4 addresses this gap.

### 3.3.5 "Steady" Flight Condition Variability

For many UAM vehicles, the variability in aircraft state when performing a 'steady' flight procedure is expected to be greater than that for conventional aircraft. Many UAM vehicle concepts feature multiple propulsion systems that are typically lightly loaded, resulting in greater sensitivity to small atmospheric disturbances that require rapid and near constant adjustments to maintain their flight condition. For many UAM vehicle designs, gusting winds or atmospheric turbulence are likely to elicit a more pronounced impact on the noise sources and their directivity compared to conventional aircraft. For example, if rotational rate-control is employed for multirotor systems, the peak noise level may vary significantly between a zero-wind condition and with light winds. UAM operations within urban environments are expected to exacerbate these effects, due to the prevalence of large unsteady flow fields and elevated turbulence levels.

The practical implications of this variability and the associated measurement uncertainty must be better understood. Tighter tolerances on aircraft control state, more stringent requirements for test day meteorological conditions, additional test repetitions, or longer data records for hover measurements may be necessary to reduce uncertainty. Reducing the variability will improve the estimate of the mean and reduce the uncertainty bands. Conversely, for certain research purposes it may be desirable to capture the full spread of acoustic variability for any given flight condition. Assessment and modeling of human (psychoacoustic) perception of UAM operations may involve sound quality metrics, some of which, like tonality and roughness, require pressure time histories to be computed. Capturing the variability in acoustic pressure time histories can help predict differences in perception using response models derived from sound quality metrics, e.g., Ref. [136]. This approach will require a much larger dataset.

This gap relates to the open 2020 recommendation SG2-2020-R4. Additionally, new recommendations SG2-2025-R1 and SG2-2025-R4 address this gap.

### 3.3.6 Most Impactful Operating State

For conventional fixed-wing aircraft in the airport environment, the maximum levels arise either during takeoff (at maximum weight with the propulsors operating at, or near, full power) or on approach (when the vehicle is in a 'dirty' configuration), and measurements at the certification points capture these levels. For rotorcraft, acoustic measurement procedures have been sculpted through years of experience such that they measure the noisiest operating state for these vehicles. For example, BVI noise is a highly directional, dominant noise source for rotorcraft on approach. Hence, relevant certification procedures (see Table 1) prescribe a 6° descending glideslope that explicitly aims to capture this noise generation mechanism. For UAM aircraft, defining what constitutes the noisiest operating states may be difficult to achieve, especially for novel configurations. Though sufficiently validated acoustic models may shed some light on the matter, it is likely that test matrices for UAM aircraft will be significantly more extensive relative to conventional aircraft, particularly during the early stages of development.

Generally, conditions chosen for acoustic measurements should be representative of operating conditions relevant to the aircraft type. At a minimum, a full flight plan including takeoff, cruise, approach, landing, and any near-ground taxiing and ground operations should be considered – each respectively representative of the most common procedures for that vehicle. This flight plan should also be consistent with the manufacturer's flight manual or preprogrammed routes. However, difficulties may arise in defining what constitutes truly representative flight conditions, particularly for vehicles with excess degrees of freedom that are able to achieve the same flight condition through various parameter combinations. Different original equipment manufacturers (OEMs) are also likely to have dissimilar approaches for dealing with these excess degrees of freedom. As such, the absolute noisiest operating state that may be technically realizable in flight, within the realm of a vehicle control system, may not be the noisiest flight state that is realistically and operationally feasible.

Noise certification and research testing will necessitate a more thorough understanding of the control law definitions. Variable and selective noise reduction systems, either automatically implemented in the control algorithms or through manual pilot intervention, may see more widespread adoption. However, assurance is needed that typical procedures and control laws employed during testing and certification will not be vastly amended later to realize some performance or cost benefit at the expense of increased noise. Conversely, given that the UAM market is evolving at a rapid pace, major operational changes may be necessary at some point in the lifetime of any specific vehicle. Manufacturers and regulators should coordinate such procedural modifications to provide an opportunity for appropriate review. See Sections 5.2.1 and 5.3.1 for an in-depth discussion of current practice and gaps in noise certification.

This gap relates to the open 2020 recommendation SG2-2020-R3. Additionally, new recommendation SG2-2025-R2 and SG2-2025-R4 address this gap

### 3.3.7 Expanded Flight Envelope Degrees-of-Freedom

Because many UAM vehicle concepts often employ many rotor/propulsor systems, obtaining noise measurements for all possible operating states is impractical. Test matrix design should be aided by the best available modeling tools in coordination with vehicle manufacturers to identify likely operating states. Test campaigns and comparisons should consider the large variation between vehicles, given varying capabilities and flight envelopes. Care will be required to ensure testing is both suitable for a given vehicle and that it records necessary data to allow comparison with suitably similar vehicles. Parameters known to be important for acoustic prediction tools (e.g., tip speeds, advance ratio, thrust coefficients, etc.) should be noted to the extent possible. Ideally, the noise produced by these aircraft can be parameterized per vehicle class or vehicle type in accordance with common definitions and categorizations, see Section 1.2.3. Measurement procedures should be devised to ensure that noise parameterization is properly recorded. Assessments can then be made on the efficacy of the parameterization, along with other objective parameters, to describe human noise response, as discussed in Section 4.3.1.1.

This gap relates to the open 2020 recommendation SG2-2020-R4. New recommendations SG2-2025-R1 and SG2-2025-R4 also address this gap.

### 3.3.8 Piloted, Semi Autonomous, and Fully Autonomous

Because many of the UAM vehicles being proposed involve some level of autonomy, it will be important to consider the influence of this autonomy on the noise generated by these aircraft. At the very least, additional instrumentation onboard these UAM aircraft may be required, compared to conventional aircraft, so that the true state of the vehicle is known. In many instances, the instrumentation requirement needed to successfully implement autonomous operation may make this very simple.

New recommendation SG2-2025-R4 addresses this gap.

### 3.3.9 Lack of Full-Scale Acoustic Flight Test Data

The lack of full-scale acoustic flight test data is a major impediment to the development of testing procedures, modeling and prediction efforts, and regulatory processes (see Section 5.3.1.1). Recommendations SG2-2025-R1 and SG2-2025-R2 are intended to help address this gap.

NASA has made acoustic measurements of a Joby Aviation pre-production prototype [137] and hover measurements for the Moog S-250 research vehicle [111]. Under a NASA-funded effort, Blue Ridge Research and Consulting partnered with The Pennsylvania State University to acquire measurements for the Archer Aircraft. At this time, the data from the Archer test are not publicly available. All these studies have limited scope and flight conditions.

There is also a lack of a common data interchange format for noise hemispheres and associated experimental results. The adoption of a common format would aid industry in addressing community noise effects, modeling and prediction efforts, and regulatory harmonization. New recommendation SG2-2025-R5 addresses this gap.

## 3.4 Recommendations

### 3.4.1 2020 Recommendations

Several practices commonly used across the aeronautics industry should be strongly considered for near-term testing or future standardization.

SG2-2020-R1. Similar test environmental constraints (e.g., ambient levels, benign meteorological conditions) to those discussed in Annex 16 and Part 36, such as precise corrections for navigation error and atmospheric losses, are highly recommended for all tests conducted to measure UAM vehicle noise. **[Closed, see Annex 16 Part [7] ]**

SG2-2020-R2. Significant on-aircraft instrumentation and monitoring of the vehicle state may be required due to varying levels of autonomy and potential increase in degrees-of-freedom of the flight envelope. **[Closed – see discussion in Ref. [119] ]**

SG2-2020-R3. Establishing what is considered the "worst" case or the noisiest mode the vehicle will fly (under automatically controlled Variable Noise Reduction System (VNRS) provisions [138]) will be a challenge, given the large variety of aircraft configurations. Additional work is recommended to define appropriate methods to evaluate acoustic dependence and variability on the vehicle state, and will likely require extensive testing (potentially supplemented with validated models). **[Open]**

SG2-2020-R4. Existing test and certification procedures should not be considered adequate to fully characterize the acoustic impact of a given UAM vehicle. For helicopters, certification measurements have often proved insufficient (due to the sparsity of microphones and the number of conditions measured) for use as input into noise prediction models. Therefore, a full assessment of anticipated UAM aircraft flight performance and operational environments is recommended to support the development of any future certification procedures and/or standards. **[Open]**

SG2-2020-R5. Close collaboration between stakeholders (including manufacturers, researchers, and certification authorities) is recommended in the development of new measurement approaches. This is especially important due to the rapid growth of this new industry and class of vehicles. **[Closed – superseded by SG2-2025-R3]**

SG2-2020-R6. Due to the potential importance of noise directed along the horizon and above the aircraft, it is recommended that measurements above the aircraft be investigated to understand their relative importance. Extreme care should be taken to ensure measurements are not corrupted by ground reflections. **[Closed – see discussion in Ref. [119] ]**

SG2-2020-R7. For many decades, four-foot-high tripod-mounted microphones have been the standard for most certification measurements. This has the unintended consequence of making measurements much more sensitive to local ground conditions, particularly for aircraft noise with dominant tones. Ground-plane measurements can offer data to the noise modeling and noise prediction communities that are uncontaminated by reflections (if desired, reflections can be added to ground-plane measurements in postprocessing to simulate an above-ground-level response). Thus, it is recommended to use flush mounted or inverted microphones over a rigid ground plane to enable widespread application of the acquired data. **[Closed – see discussion in Ref [119] ]**

### 3.4.2 2025 Recommendations

Because UAM aircraft configurations and operations are far more diverse than those of conventional aircraft, innovative measurement methodologies are required to adequately capture the acoustic signature of these aircraft. While best practices from ground and flight testing for conventional aircraft should be applied to any UAM aircraft measurement, new and diverse testing is required. It is recommended that:

SG2-2025-R1. Full-scale flight testing for a broad range of vehicle types be conducted to fully characterize landing and takeoff noise of UAM vehicles, as it is expected that this segment of flight will contribute to community noise. Eventually, performance-based metrics and standards need to be developed.

SG2-2025-R2. Flight testing focused on assessing noise effects on communities be conducted using both existing and innovative procedures.

SG2-2025-R3. Full-scale acoustic flight testing for UAM vehicles evolve to keep pace with evolving industry and regulatory needs.

SG2-2025-R4. As the efficacy of metrics and objective parameters relating UAM aircraft noise to human response become established, measurement techniques and best practices should be appropriately refined and disseminated throughout the wider community.

SG2-2025-R5. A standard exchange format be adopted for full-scale vehicle datasets to ease interoperation with agencies, companies and researchers. Recommendations should be developed that encompass data format and metadata type to smooth these interactions.

Note: Recommendations SG2-2025-R1 – SG2-2025-R5 align with recommendation 4.3 in the AAM National Strategy [8].

# 4 Human Response and Metrics

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## 4.1 Introduction

UAM introduces unique acoustic characteristics, such as the distinct sounds generated during hovering, rapid transitions between flight modes, multiple rotors operating simultaneously, and installation effects arising from rotor-fuselage and rotor-rotor interactions. Vertiports and flight paths may be located closer to residential neighborhoods and dense urban communities than existing aviation infrastructure and operations. UAM also offers the possibility of significant mitigation of annoyance through vehicle and operational designs that may not be available with conventional aircraft. These factors may influence annoyance, detectability, and overall community response in ways not observed with conventional aircraft. Additionally, as UAM operations scale up to include more aircraft, flight paths will be structured for operational safety, further shaping noise exposure patterns and community effects. Accounting for these evolving operational characteristics when gathering UAM vehicle noise human response data is critical to accurately assessing the implications of UAM noise.

The 2020 white paper [1] noted the lack of data on noise metrics relevant to both vehicle design and the assessment of community noise effects. Some data on UAM vehicle noise responses are now available, and this progress is described in Section 4.2. Gaps remain in quantifying the efficacy of various metrics to describe the annoyance responses to UAM vehicle noise. In Section 4.3, emphasis is placed on understanding the efficacy of various metrics and objective parameters, including the number of flyover events, to describe UAM vehicle noise responses. In addition, community noise response surveys involving actual aircraft flights can establish the applicability of long-term exposure metrics and provide valuable insights to inform decision-making by manufacturers, aviation regulators, and local land use authorities.

This section differentiates laboratory psychoacoustic testing from community noise surveys, and short-term from long-term noise exposure using the following definitions and context:

- Laboratory psychoacoustic testing is meant to reveal a relationship between the short-term noise exposure of UAM vehicles and human response. Short-term noise exposure can be described by durations from immediate to next day and by responses occurring immediately or within approximately 24 hours following the noise exposure [139].
- Community noise surveys can be used to produce long-term exposure-response relationships between UAM vehicle noise exposure and human response that, in turn, can be used to establish noise regulations and to inform land use policy (see Section 5). Long-term noise exposure can be described with durations of weeks, months, or years [139].

## 4.2 Current Practice

This subsection considers human response and metrics as they relate to short-term and long-term UAM vehicle noise exposure.

### 4.2.1 Response to Short-Term UAM Vehicle Noise Exposure

#### 4.2.1.1 Current Practice Related to 2020 Recommendations

This subsection describes progress made toward the 2020 recommendations (see Section 4.4.1) related to short-term UAM vehicle noise exposure through citation of some contemporary research.

**Recommendation SG3-2020-R1 (Acquire Vehicle Acoustic Data)**

This recommendation is considered closed based on sufficient initial data captured by the following four efforts. The first is a UAM vehicle noise human response study that was motivated by consensus among the UNWG that such a study be performed. A preliminary feasibility test using sUAS and ground vehicle noise explored the efficacy of test methods to gather responses from geographically distinct test participants [140]. Initial results for the main UAM vehicle noise human response study test, called VANGARD, were given in [141]. Another laboratory test on UAM vehicle noise response gathered from geographically diverse test subjects compared UAM vehicle noise response to helicopters and turboprops [142]. These testing efforts to gather responses to UAM vehicle noise from different communities required collaboration with OEMs to gather UAM vehicle sound stimuli. A third effort, called the Helicopter and UAM Laboratory Comparison (HULC) psychoacoustic test [143], used UAM vehicle sounds gathered through collaboration with OEMs to compare lightweight helicopter noise response with UAM vehicle noise response. Lastly, recent work [144] by the DLR in collaboration with TU Delft evaluated the noise emissions of a UAM vehicle with distributed propulsion (including 26 electric ducted fans) and considered variations in the rotational speed of the ducted fans. Although the recommendation is considered as closed, collaboration with OEMs to gather UAM vehicle sound stimuli for future laboratory psychoacoustic testing continues.

**Recommendation SG3-2020-R2 (Process to Catalog Ambient Sound)**

This recommendation is considered closed based on the following efforts. Methods to record and document ambient soundscapes were given in Ref. [145]. Further, ISO 12913 [146] provides standards for assessing soundscapes. These standards have been employed (within the Impact and Capacity Assessment Framework for U-Space Societal Acceptance project [147]) in designing a series of soundwalk studies undertaken in Salford (UK) [148], the Isles of Scilly (UK) [149], and Athens (Greece) [150] using live demonstrations for controlled addition of sUAS noise to investigate the relationship between several sUAS parameters and background sound conditions. Psychoacoustic testing on sUAS and helicopter noise has adopted high-fidelity spatial recording and reproduction techniques, such as 3D ambisonics, to represent ambient sound with realistic spatial rendering [151-154]. The efforts that closed this recommendation may be leveraged to simulate/auralize ambient sound environments for human noise response testing, communication, or vehicle design assessments.

**Recommendation SG3-2020-R3 (Compare Response to UAM Vehicle Noise with Response to Other Aircraft Noise)**

This recommendation is considered closed by virtue of efforts documented in Refs. [142,143], along with initial results in Refs. [36,155] that compare UAM vehicle noise response to that of helicopter noise and sUAS noise.

**Recommendation SG3-2020-R4 (Develop and Validate Models for Detectability, Noticeability, and Annoyance)**

Inclusion of background sound in psychoacoustic testing can increase realism and the ecological validity of experiments [156]. The effects of background sounds on annoyance have been investigated for sUAS, helicopter noise, and wind turbine noise, which can help inform testing on UAM vehicle noise response within different background sounds [148,150,151,154,157-161]. There are five main hypotheses for how background sounds may affect annoyance to a (novel) UAM vehicle noise source:

1. Masking Discount Hypothesis: The background sound may partially or completely "mask" the UAM vehicle noise, lowering or eliminating, the annoyance response.
2. Desensitization Hypothesis: The presence of the background sound may desensitize the listener to UAM vehicle noise, even if the UAM vehicle noise is new and unexpected, lowering the annoyance response.
3. Sensitization Hypothesis: The background sounds may sensitize a listener so that a noise source causes more annoyance than it would if the background sounds were not present.
4. Blending Hypothesis: If the noise is still audible but unsurprising in the context of the background sounds, the UAM vehicle noise source may "blend" with that context, lowering annoyance.
5. Referential Sound Hypothesis: Annoyance to UAM vehicle noise is influenced (lowering or raising) by relating it to existing known sound sources that are presented in the background.

It is possible that most or all five of the Background Sound Response Effect Hypotheses on UAM Vehicle Noise Response are correct, and that they may contradict, counteract, or interact with one another in complicated real-world scenarios.

Out of the five hypotheses, evidence has been gathered for the Masking Discount Hypothesis regarding UAM vehicle noise response. Results from Ref. [142] provided evidence of the Masking Discount Hypothesis, but the significance of the results depended on the UAM vehicle noise levels and specific background environment. The model in Ref. [162] uses signal detection theory [163] and showed the rates at which an individual's annoyance to UAM vehicle-like sound is reduced in the presence of background sounds. The annoyance model [162] was applied in Ref. [164], but requires validation. Therefore, progress has been made on SG3-2020-R4, but the validation remains open.

**Recommendation SG3-2020-R5 (Quantify Transmission of UAM Vehicle Noise Indoors)**

A psychoacoustic test [165] investigated the differences in perception for sUAS noise between indoor and outdoor listeners. However, because there have been no known efforts on indoor transmission of UAM vehicle noise, the recommendation remains open.

**Recommendation SG3-2020-R6 (Use Human Response Measures in Perception-Influenced Design)**

Progress has been made on this recommendation. Contemporary laboratory psychoacoustic testing has found evidence that sound quality metrics, in addition to loudness, play an important role in the annoyance response to UAM vehicle noise [166-169]. Ref. [144] also evaluated UAM vehicles with distributed propulsors using sound quality metrics. An initial UAM vehicle noise annoyance model was developed [136] using results from a psychoacoustic test [166], and a method to assess levels (in terms of sound quality metrics [170]) that produce just-noticeable differences in annoyance was also explored. Verifying and validating the predictive models through additional psychoacoustic testing remains a focus of UAM vehicle noise human response research. Predictive models of UAM vehicle noise response can help develop or assess the potential applicability of long-term exposure metrics and inform community noise surveys. The initial applications of these predictive models can be for perception-influenced design (PID) [171] of vehicles [144,172] and their operations.

**Recommendation SG3-2020-R8 (Explore Differences in UAM Vehicle Noise Perception Between Communities)**

This recommendation is considered closed with the completion of the VANGARD test [141].

**Recommendation SG1-2020-R4 (Continued Development of Auralization Tools)** – Realigned from Section 2.4 of Ref. [1]

Progress has been made on this recommendation. Auralization of UAM vehicle noise is important for understanding human response and communicating noise effects. When measured/recorded stimuli are unavailable or are challenging to obtain, auralizations of UAM vehicles can be generated from aerodynamic and acoustic numerical predictions to provide sound stimuli for laboratory psychoacoustic testing and in subsequent PID processes. As such, it enables listening to virtual designs (such as UAM vehicles) that may not physically exist [173].

Some findings from drone noise auralization [153,174] highlight the importance of including amplitude and frequency modulations to achieve perceptual plausibility. This aspect is also expected to play an important role in the auralization of UAM vehicles. The importance of including broadband noise modulations in rotorcraft auralizations was explored in Refs. [175,176]. Methods to synthesize these modulations [177-180] have been introduced in auralization tools. These techniques have been coupled with the synthesis of rotor loading and thickness noise (see Section 2.1.1) to generate auralizations for psychoacoustic testing. Other auralization techniques to generate sounds of distributed propulsion systems have also been developed [144,181,182].

The takeoff and landing operations of UAM vehicles will likely involve transitioning through multiple flight conditions or trimmed states. With UAM vehicles operating closer to communities than conventional aircraft, generating transitional flight sounds is needed in UAM vehicle auralizations. Some progress has been made in auralizing transitional flights [183], but the techniques need to be further developed and validated.

To more accurately capture the noise exposure from UAM vehicles, sound propagation through urban environments is a necessary capability. Such auralizations need to include reflection and diffraction effects. Ref. [86] found the latter to be challenging, but others have made progress on modeling them [184].

The combined use of auralizations and visualizations has been limited [151,152,185] but may become important for UAM vehicle psychoacoustic testing involving non-acoustic factors and for community engagement (see Section 5.2.3).

#### 4.2.1.2 Other Contemporary Laboratory Research and Tool Development

Other laboratory psychoacoustic testing efforts on short-term response to UAM vehicle noise exposure have been conducted that do not directly address a Ref. [1] recommendation. These tests are important to improve the understanding of the effects of UAM vehicle noise on people and include:

- Investigations into how the time structure of UAM vehicle flyovers affects annoyance response [186,187].
- Investigations into the effects of context on subject responses. Examples of providing context include asking study participants to think about being at their home, another specific location, or time of day. Results from studies on the contextual effects to drone noise response may be applied to UAM vehicles [140,160].

**Additional Tools for Calculation of Sound Quality Metrics**

Related to recommendation SG3-2020-R7 are improvements to metric calculation tools. While tools like the ArtemiS SUITE from HEAD Acoustics [188] and MoSQITo [189] (Python®-language based) are available to compute sound quality metrics used in laboratory psychoacoustic testing, additional tools to compute these metrics have become available. These tools include the NASA Auralization Framework (NAF) [190] Psychoacoustic Analysis Library [191] and the MATLAB®-based Sound Quality Analysis Toolbox (SQAT) [192].

### 4.2.2 Response to Long-Term UAM Vehicle Noise Exposure

**Purpose of Community Noise Surveys**

Community noise surveys are performed to establish long-term exposure-response relationships to inform regulatory limits for vehicles and communities and land use policies, e.g., Ref. [193]. Stevens et al. [194] and Eldred [195] showed how community noise response is affected by factors other than the physical characteristics of the sound, including respondents' association with the source of the noise, community outreach, and whether the noise is new versus long standing, in which case adaptation may be an important factor. Such effects may be difficult to capture in laboratory testing but may be captured in community noise surveys.

### Types of Community Noise Surveys

Community noise surveys, including noise exposure from real aircraft operations, may be either observational or staged. Observational surveys are those conducted in areas where ongoing aircraft activity already serves as the mechanism for generating the noise exposure. Staged noise surveys, on the other hand, are those conducted where the aircraft of interest are operated explicitly for the purpose of generating the noise exposure for the survey area. Examples of these two types of surveys are the observational FAA Neighborhood Environmental Survey (NES) and the staged NASA X-59 Quesst Community Survey Campaign currently undergoing planning (see Section 4.2.2.2 and Appendix D.2).

### Survey Scale, Representativeness, and Applicability

Small-scale community noise surveys (e.g., single community or metro area) can offer useful insights regarding exposure-response relationships for aircraft noise, but the results of such surveys may not be applicable to other communities. Additionally, small-scale surveys may not include noise exposure from a sufficiently broad representation of UAM vehicle types. Large-scale surveys (e.g., multiple metro areas / nationwide) allow for larger sample sizes and capture a broader range of respondent demographics and attitudes. Furthermore, the noise exposure will include the varied vehicle types in operation.

### Noise Exposure Determination and Spatial Association

Community noise surveys can also differ in the methods used for determining the noise exposure and the association of the exposure to the locations in which survey participants experience aircraft noise. Methods for determining noise exposure quantities can be measurement-based, modeling-based, or a combination of both. Measurements alone are unlikely to provide sufficient geographic resolution to support surveys with many participants spread over a large area. Measurements are also susceptible to contamination from other ambient sound sources. As such, large-scale community noise surveys typically rely on modeling or modeling supplemented with noise measurements to determine noise exposure (see Section 5.2.2.3). For the NES, the noise exposure was calculated using airport noise modeling, and the locations were limited to the survey participants' place of residence. For the X-59 Quesst survey (Section 4.2.2.2), daily noise exposure will consist of a few sonic booms and will be determined through a combination of measurements and modeling and calculated for individual events at the location where each participant experiences that event (see App. D.2 for additional concerns with this method). For airport noise and potentially vertiport noise, where flights can frequently occur throughout the day, the burden on participants responding to surveys in a timely manner after every event may be impractical. Such distinctions in survey design should be considered when comparing exposure-response metric results across different survey efforts.

### Survey Instruments and Communication Tools

Standards for socio-acoustic questionnaires for community noise surveys are described in [196] and [197], although they have not yet been applied to UAM community noise surveys.

### Exposure Metrics for Community Noise Exposure

Metrics like the day-night average sound level ($L_{dn}$, also DNL) or $L_{Aeq}$ have long been used to assess community noise exposure. These metrics are A-weighted, which approximate perceived loudness using early equal-loudness contour models and are favored for their decades of proven efficacy despite, and in addition to, their computational and measurement simplicity. The FAA has relied on $L_{dn}$ in key analyses, including those based on the Schultz curve [198] and the more recent NES, both of which rely on $L_{dn}$. The FAA adopted the $L_{dn}$ metric in 1980, following the Aviation Safety and Noise Abatement Act (ASNA) of 1979, which called for the development of standardized noise exposure metrics.

Under current FAA policy, supplemental metrics are used to improve public understanding of aviation noise, not for decision-making [199]. The International Institute of Noise Control Engineering (I-INCE)

Supplemental Metrics Report [200] notes that many commonly used noise metrics were chosen, in part, for their practical considerations—such as ease of measurement and regulatory precedent—and not just because they comprehensively describe how communities respond to noise. Cumulative metrics like $L_{dn}$ simplify a complex noise exposure into a single number, and some individuals will find this number to be not representative of their experience or hard to interpret [201]. Thus, the use of multiple metrics such as the number of awakenings, the number of events above a threshold noise level (NANL), and the time above a threshold noise level (TAL) could be used in community noise surveys and can characterize aspects of noise exposure such as event count, duration above thresholds, and exceedance levels; furthermore, time-of-day weightings could also be applied.

#### 4.2.2.1 Current Practice Related to 2020 Recommendations

**Recommendation SG3-2020-R7 (Comprehensive Evaluation of Supplemental Metrics)**

There have been no community noise surveys directed at UAM to date to understand the efficacy of supplemental metrics, so this recommendation remains open. However, preliminary steps have been made toward that recommendation, including the VTOL Paris 2020 project and NASA/FAA preparations for eventual UAM vehicle noise community response survey(s).

The VTOL Paris 2024 project (see Appendix D.1) was launched in 2020 by ADP (Paris Airports) with the objective of providing an experience of VTOL commercial flights above Paris in 2024. Despite a relatively negative community response (via online inquiry) to the creation of the vertiport along the Seine, its creation was authorized by Minister of Transport of France. The project ultimately concluded without any flight operations, due to delay in the development of the aircraft.

In 2022, NASA and the FAA solicited feedback on a set of candidate objectives for a community noise survey to establish a long-term exposure-response relationship for UAM vehicle noise [202]. These included understanding:

- The effect of the number and tempo/time structure of operations on annoyance.
- The efficacy of $L_{Aeq}$-based metrics like $L_{dn}$ and the community noise equivalent level ($L_{den}$, or CNEL).
- Response differences by setting, e.g., proximity to a vertiport.
- How communities react to the introduction of UAM vehicles.
- Changes in average background sound levels with the introduction of UAM.
- Differences between UAM vehicles and other aircraft when considering sleep disturbance and treatment of noise-sensitive sites.
- The effect of noise on communities from different UAM vehicle operations.

More recently, NASA, in cooperation with the FAA and Department of Transportation (DOT) Volpe Center, developed a scoping document as a preliminary step toward a multiyear project plan with the following objectives:

1) Formulate a technical methodology, develop needed analytical tools, and generate necessary data to inform subsequent efforts by the FAA to conduct community noise survey(s)/test(s) and develop a nationally representative long-term exposure-response relationship for UAM vehicle noise in relation to other aircraft noise.

   Given the desire for comparability with other (existing) aircraft noises, an NES-like study (see Section 4.2.2.2) was envisioned with the noise exposure measured by $L_{dn}$ and the response measured by the percentage of the survey population as being highly annoyed (%HA). Other measures of noise exposure and response may also be investigated.

2) Investigate the relative contribution of sUAS as they relate to the UAM community noise environment.

The second objective was included because it may not be possible, or even meaningful, to establish an exposure-response relationship for UAM vehicle noise without also considering the contribution of sUAS for two main reasons: i) the two aircraft types may operate in the same environment and ii) the public may not discriminate between the two aircraft types when completing noise surveys.

The technical review of the scoping document was conducted by three independent review teams composed of subject matter experts having demonstrated experience with aircraft community noise and with conducting aircraft community response surveys at a regional or national level. The scoping document and reviews were published in Ref. [203]. The proposed effort is aligned with recommendation 4.3 of the AAM National Strategy [8] and the associated plan to expand research to understand how communities will respond to noise from AAM operations [9].

#### 4.2.2.2 Other Contemporary Community Noise Surveys

Contemporary community noise surveys related to commercial subsonic and supersonic transport aircraft and to sUAS are discussed in Appendix D.2. Lessons learned from these efforts that could benefit planning and execution of future UAM vehicle noise surveys include the following:

- The FAA conducted a nationwide survey, the NES, to assess annoyance related to aircraft noise [204]. Lessons learned relevant to UAM vehicle noise studies include:
  - Continued assessment of the efficacy of $L_{dn}$ to describe annoyance response but consideration of event- or time-based metrics, e.g., NANL, and time-sensitive metrics, e.g., TAL, and
  - Inclusion of responses from communities experiencing overflights from multiple vertiports in addition to communities near vertiports.
- Using the NASA low-boom flight demonstrator aircraft, X-59, the NASA Quesst mission [205] plans to gather representative exposure-response data to inform regulators in their efforts to potentially develop noise standards for overland supersonic flight. Tools and methods developed for the Quesst mission that may be applicable to future UAM vehicle noise surveys include:
  - Exposure-response statistical models, including methods for combining results from multiple community noise survey test sites,
  - The web-based survey instrument used to gather responses,
  - Methods for estimating single-event and cumulative noise exposure via a combination of ground-based field measurements and physics-based predictions, and
  - Efficient methods for automated data collection, display, and analysis.
- Community responses to drone noise have been gathered in the United States [206,207], in Australia [208], and in the European Union [209]. Applicable lessons learned for UAM vehicle noise include:
  - Responding to community noise issues helped to secure further deployment permits (see Appendix D.2). Not responding prevented additional operations,
  - A need to continue to investigate the efficacy of conventional single-event metrics (e.g., $L_{AE}$, EPNL) to describe responses from community surveys,
  - A need to report on other noise metrics that characterize short-term flyover events, like peak sound levels, in addition to $L_{AE}$ and/or EPNL, to help interpret community noise surveys and inform decision-making, and
  - Social acceptance surveys can ask participants about their thoughts on UAM vehicle noise without exposing them to the noise. It will be beneficial to relate the results of social

acceptance surveys to analyses of annoyance responses, including uncertainty quantification, so subsequent social surveys may be used in situations where participants cannot or are unable to be exposed to UAM vehicle noise.

## 4.3 Gaps

### 4.3.1 Response to Short-Term UAM Vehicle Noise Exposure

Many factors can influence the response to short-term UAM-vehicle noise exposure. As mentioned in Section 4.2.1, progress has been made to improve the understanding of these factors and their relationship to UAM vehicle noise annoyance. Remaining knowledge gaps in human response to UAM vehicle noise include the following four broad constructs:

- Single-Event Noise Perception: Assessment of the efficacy of objective parameters that describe human annoyance response to single-event UAM vehicle noise (see Section 4.3.1.1).
- Persistent Factors: Understanding how persistent situational and attitudinal factors affect annoyance to short-term UAM vehicle noise (see Section 4.3.1.2).
- Number of Events: Characterizing and modeling how the number of events and their time structure affect the annoyance response (see Section 4.3.1.3).
- Concurrent Background Noise: Quantifying how annoyance changes to UAM vehicle noise in the presence of background sounds (see Section 4.3.1.4).

Gaps within each of the constructs can be addressed with laboratory psychoacoustic testing of response to short-term UAM vehicle noise. The objectives and design of specific tests will not be discussed, but the content in the following subsections may inform objectives and design of such tests. The relationship between these constructs and the design of community noise surveys is noted where relevant.

#### 4.3.1.1 Single-Event Noise Perception

Broad Research Objective: Assess the efficacy of objective parameters to describe the annoyance for single-event UAM vehicle sounds.

Additional Details: Many objective parameters correspond to single-event UAM vehicle sounds. These parameters include conventional noise metrics, like $L_{AE}$, and perception metrics like sound quality metrics. Low-frequency UAM vehicle sounds that can cause vibration at a listener are important to consider. Other parameters include operational scenarios that can be described quantitatively with variables like air speed, climb angle, and turn radius. Objective parameters can also include non-acoustic factors that persist only within the duration of single-event UAM vehicle sounds. ISO/TS 16755-1 [210] gives some examples of non-acoustic factors, but one example is a visual of the UAM vehicle. High-level goal HLG-2020-3 and recommendations SG3-2020-R3, SG3-2020-R4, and SG3-2020-R6 sought to advance the ability to use noise metrics to describe the annoyance response to UAM vehicles. Progress has been made on developing this capability (see Section 4.2.1). The gap now is to assess which of these metrics and other objective parameters best describe the annoyance response to UAM vehicles. An understanding of the most important parameters for describing the annoyance response to any UAM vehicle and operation might be beneficial. However, it is possible that certain objective parameters describe the annoyance well in specific cases, like in cruise phases, while other parameters describe it well in other specific cases. In addition to assessing the efficacy of several objective parameters, a framework for understanding the situations and context in which each objective parameter describes the annoyance response is needed. Other examples of objective parameters to consider for their efficacy in describing short-term UAM vehicle noise are:

- Sound propagation factors such as atmospheric and weather conditions, which not only affect the sound propagation but also vehicle trim.
- Perceptual thresholds, such as which levels of a metric lead to noticeable annoyance differences, for single and multiple UAM vehicle noise sources [136].

- 'Onset rate'. With UAM vehicle departure and approach operations being closer to communities compared to other commercial operations, it is possible that the sounds may rise to their peak levels faster, influencing perception, and may require a response penalty [211].
- Whether a UAM vehicle follows Fly Neighborly procedures [39] or is permitted by the Integration of Powered-Lift final rule from the FAA and associated Special Federal Aviation Regulation (SFAR).

Knowledge Gap Being Addressed: An improved understanding of the efficacy of objective parameters to describe the human annoyance response and the context in which that description is being made is needed to inform perceptually low-noise vehicle design (HLG-2025-1), assessment of noise reduction technologies (HLG-2025-2), provide descriptors for vehicle noise and operations databases (HLG-2025-3), and inform noise abatement LTO procedures (HLG-2025-4). This improved understanding can improve predictive models of UAM vehicle response. Recommendation SG3-2025-R2 addresses this gap.

Effects on Long-Term Exposure-Response Relationship Development: Inform the efficacy of metrics to short-term noise that may be used to predict long-term exposure (HLG-2025-5).

#### 4.3.1.2 Persistent Factors

Broad Research Objective: Assess the efficacy of how different persistent situational and attitudinal factors affect annoyance to short-term UAM vehicle noise and develop a framework for understanding the context in which each persistent situation affects the annoyance response.

Additional Details: Persistent factors are long-term situations that appear in a community for weeks, months, or years that, on average, may affect how the community feels towards certain noise sources and that affect their annoyance response. One example of a persistent factor is a community's existing experience with aircraft noise. Other examples include, but are not limited to, acoustical and non-acoustical factors, such as average noise level in a particular area and the perceived societal benefit of UAM vehicles, e.g., emergency operations. ISO/TS 16755-1 [210] gives examples of other non-acoustic factors that may be considered persistent, such as social factors. There have been previous investigations on the relationship between persistent factors and aviation noise annoyance [212-215]. Based on findings for other noise sources [216,217], the annoyance response to UAM vehicle noise may be reduced when they are used for the benefit of the provider/user. Where and how people live could, over time, give them a context through which they will respond to UAM vehicle noise [218].

Knowledge Gap Being Addressed: Relating quantifiable persistent factors to annoyance response and describing the context for the relationships are needed to provide descriptors for vehicle noise and operations databases (HLG-2025-3) and to inform noise abatement LTO procedures (HLG-2025-4). Establishing relationships between persistent factors and annoyance can also improve predictive models of UAM vehicle noise response. While recommendations SG3-2020-R5 and SG3-2020-R8 targeted data generation on indoor noise and response differences among communities, respectively, an assessment of which persistent factors contribute the most to describing the annoyance response is needed. Recommendation SG3-2025-R2 addresses this gap.

Effects on Long-Term Exposure-Response Relationship Development: Possible evidence for a dependence between persistent factors and the long-term exposure-response relationship can be gathered from short-term noise responses of laboratory test participants who represent communities in long-term situations. These data can be used to plan community noise surveys that test if such a dependence exists in the real world. Evidence in a community for the Desensitization and Sensitization Hypotheses, mentioned in Section 4.2.1.1, may be found with short-term noise testing by comparing responses between participants from communities with different soundscapes. A full test of the Desensitization and Sensitization Hypotheses will need to involve long-term noise responses with real community background sounds.

#### 4.3.1.3 Number of Flyover Occurrences

Broad Research Objective: Characterize and model how the number of flyovers and their time structures describe the annoyance response. Time structures refer to variables like flight frequency and intervals between individual flyovers. This characterization and modeling may complement other metrics that capture the sounds of individual flyovers.

Additional Details: The Equal Energy Hypothesis (EEH) assumes that annoyance responses to the noise from multiple flyover events can be predicted by summing the mean-square pressures of the events [201]. Studies have indicated that while metrics used by the EEH are the best first-order predictors of multiple-event response, they also show that higher-order models that weight or penalize the number of UAM vehicle flyover events perform considerably better to predict laboratory responses to multiple noise events [186,187]. However, these higher-order models are not formulated in a way that is necessarily extensible to real-world UAM situations with complicated multiple flyover time structures. These time structures may cause communities to perceive UAM vehicle flyovers as unpredictable, which may increase the annoyance response [219]. Extensible annoyance models that account for the complicated time structures of multiple flyover events need to be generated. These extensible models need to be tested to generate datasets large enough to evaluate the statistical significance of their ability to improve annoyance prediction. The following examples are parameters for extensible annoyance models of multiple flyover events that may improve the annoyance prediction of such models:

- Unequal durations between flyovers.
- Heterogeneous noise events with different UAM vehicles, durations, maximum noise metric levels, and $L_{AE}$.
- Time of day distribution.
- Operations occurring in combination with conventional commercial and general aviation aircraft.

Knowledge Gap Being Addressed: UAM vehicles are expected to operate in larger numbers and have a higher flyover cadence than conventional aircraft. Understanding the effect that the number and time structure of UAM vehicle operations will have on their noise annoyance is needed to capture how communities are more likely to experience UAM vehicle operations as operational exposure patterns change over time. Recommendation SG3-2025-R3 addresses this gap.

Effects on Long-Term Exposure-Response Relationship Development [202]:

- Inform how the number and time structure of flyovers may affect perception during community noise surveys. For observational surveys, annoyance may be modeled to help with survey site selection, for example. For staged surveys, the number and time structure of flyovers can be selected based on multiple-flyover perception models.
- Understand how exposure-response relationships may be adjusted as the number and time structure of flyover events change.

#### 4.3.1.4 Concurrent Background Sounds

Broad Research Objective: Develop validated models to predict UAM vehicle noise response in different ambient environments by testing the Masking Discount, Blending, and Referential Sound Hypotheses (see Section 4.2.1.1).

Additional Details: Complete masking of UAM vehicle noise may be predicted with reasonable confidence in simple/controlled/contrived situations, e.g., tone-in-noise-detection tasks in a laboratory environment. However, there is no validated generalizable annoyance prediction model of partial masking of UAM vehicle noise in the presence of a given ambient sound that was formed from testing the Masking Discount, Blending, and Referential Sound Hypotheses. There is also a time-varying aspect to the background sounds over any given averaging time (seconds, minutes, hours, etc.) that makes its characterization in laboratory experiments difficult. Finally, it is unknown whether a demonstrable effect of partial masking by the ambient sound in one experiment will carry over to another experiment that uses a different ambient sound. Even when partially masked, a UAM vehicle may be more perceptually distinctive in one ambient sound than another. There is nascent work in characterizing ambient sounds in terms of the multiple auditory sources that may or may not occur at one point in time (e.g., [220]), but in most practical applications, ambient sound is characterized using traditional sound engineering metrics (peak or time-averaged levels) that may not capture changes in annoyance.

Layered noise can be part of ambient sound and refers to sounds other than the UAM vehicles being intermittently introduced into the soundscape [221-224]. There have not been studies on how UAM vehicle noise is simultaneously perceived with another aviation noise source. The Masking Discount, Blending, and Referential Sound Hypotheses may all be needed to explain the response with layered noise. Studies that investigate UAM vehicle noise response may model layered noise using evidence-based data, such as those from existing noise monitors in communities surrounding many airports [225]. The rate and sound levels of jet aircraft flyovers, for example, may be introduced to simulations of UAM vehicle noise based on the flyover rate and sound levels in noise monitor data. However, see Section 3.1.1 for potential signal-to-noise ratio issues with noise monitors. Section 5.2.2 also discusses noise monitors.

The following partial list of developments can help address recommendation SG3-2020-R4 concerning the effects of concurrent background sounds on noise perception:

- Validate a general model of how a UAM vehicle will be perceived for a given background/ambient sound. If a general model cannot be validated, then a set of models for UAM vehicle noise perception in different background/ambient sound environments (e.g., urban vs. rural) will need to be validated.
- Quantify how annoyance to UAM vehicle noise is affected by locations where masking background/ambient sound levels are intermittent or contain layered noise.
- Capture the spatial component of ambient sound to account for both spatial-binaural release from masking and for perceptual veridicality and ecological validity [156].
- Refine and update how ambient sound is cataloged, as described in Section 4.2.1.2, that includes, among other ambient sound features, both the intermittent and spatial components of ambient sound, to help develop predictive annoyance models.
- In an overlap with the Number of Events construct (Section 4.3.1.3), determine the applicability of models that relate annoyance response, number of UAM vehicle flyovers, and their time structure to situations when concurrent background sounds are present.

Knowledge Gap Being Addressed: Methods and tools are needed to quantify how annoyance changes to UAM vehicle noise when background/ambient sound simultaneously occurs with (masks) the UAM vehicle noise. Recommendation SG3-2020-R4 is focused on addressing this gap and is still open. Therefore, a new recommendation regarding UAM vehicle noise response with concurrent background sounds will not be made. Additional details on this gap beyond what is mentioned in Ref. [1] are given in this subsection.

Effects on Long-Term Exposure-Response Relationship Development: Inform the selection of and account for ambient sound environments in which to perform surveys that establish exposure-response relationships.

#### 4.3.1.5 Improved Auralization Capabilities

To help address the knowledge gaps in Sections 4.3.1.1 and 4.3.1.2, progress on recommendation SG1-2020-R4 to develop auralization tools should continue to increase the fidelity or realism of UAM aircraft auralizations. Validation still needs to accompany tool development for transitional flight and broadband noise synthesis techniques. Periodic rotor loading and thickness noise and broadband rotor self-noise are considered prominent noise sources, but inclusion of other UAM vehicle noise sources, many of which are described in Section 2.1.1, can potentially increase auralization realism. Continued progress on activities supporting recommendations SG1-2020-R1, SG1-2020-R2, SG1-2020-R3, SG1-2020-R5, SG1-2020-R6, SG1-2025-R1, and SG1-2025-R2 will inform which UAM vehicle noise sources may be important to include in auralizations and if improvements to source noise predictions require updates to sound synthesis techniques. Progress on recommendation SG2-2020-R3 can also inform on the noisiest flight operations to auralize.

Developers of UAM vehicle auralizations should communicate where the latest updates to machine learning algorithms may improve auralization capabilities. Other developers and researchers need to understand algorithm trade-offs in terms of time/frequency resolution, achievable signal fidelity, and preprocessing requirements. Such communication should convey the limitations (or sufficiency) and the cost of training data for these algorithms.

Continued research and development are needed to auralize UAM vehicle noise in simulated urban environments with more accurate reflection, diffraction, and refraction effects. Such sounds can more accurately communicate how the lived experience of a community will be affected by UAM vehicle noise and support SG4-2020-R5.

It was proposed to UNWG participants in the Human Response and Metrics area of interest that reference simulated urban and vertiport locations be specified in an accessible database. These references can provide a common set of complex propagation environments to help compare results from different laboratory studies that use UAM aircraft auralizations in urban or vertiport environments. No consensus was reached by the UNWG participants on the utility of reference simulated locations, although there was consensus on the need for urban sound propagation tools. There was also consensus that, if a study or sound demonstration used a simulated complex urban environment, the details of the urban environment should be made available so that comparisons could be made if necessary.

The requests, needs, and consensus described in this subsection are captured in new recommendation SG3-2025-R4 that supersedes the previous recommendation SG1-2020-R4.

### 4.3.2 Response to Long-Term UAM Vehicle Noise Exposure

Community noise surveys that establish long-term exposure-response relationships to UAM vehicle noise can only be performed once UAM vehicles are operating over populations for extended periods of time. Consequently, there is a knowledge gap in how communities will respond to UAM vehicle operations. Knowledge gained from laboratory psychoacoustic testing, as discussed in Section 4.3.1, however, may be used to guide the design of eventual surveys. This subsection identifies several factors that must be considered in the design and execution of community noise surveys, including those for quantifying the noise exposure and those for assessing the response. The consensus in this subsection formed the new recommendation SG3-2025-R1.

#### 4.3.2.1 General Considerations for Conducting Community Noise Surveys

A survey design is needed to ensure that community noise surveys accurately reflect how people will respond to UAM vehicle noise under real-world operations. As part of any survey design, the study objective must be clearly defined and consideration of site selection, the number of surveys, and survey reassessment are required and should be informed by the constructs in Section 4.3.1.

**Site Selection**

Some factors to consider in site selection include:

- Assessment of operations:
    - Are existing operations well-established? If not, then what is the likelihood of future UAM vehicle operations?
    - Are existing operations appropriate for the survey, e.g., the number and time structure of operations (schedules), the homogeneity of the fleet (diversity of noise sources), and flight profiles?

    - Mix of operations if testing for perception associated with medical transport/other emergency operations, e.g., firefighters or police.
- Effects of pre-existing aviation noise: Is the survey intended to study only UAM vehicle noise effects or all aviation noise, including UAM vehicle noise?
- Examination of land use patterns (e.g., proximity to vertiports, flight corridors, noise-sensitive areas including schools, places of worship, parks, and exposure to aircraft noise vs not being exposed to aircraft noise).
- Consideration of demographic representativeness at survey sites.
- Consideration of the vertiport type and who is affected, e.g., communities near airports, communities near vertiports, and overflown communities.
- Consideration of ambient sound conditions and contextual factors including:
    - Assessment of background sound levels at potential/selected survey sites that are current and validated with measured data in at least some locations.
    - Consideration of temporal factors (e.g., time of day, peak traffic periods, seasonal variations).
    - Documentation and measurement of non-aviation noise sources.
    - Layering effects (see Section 4.2.1.2).

**Number of Surveys**

Multiple community noise surveys are likely necessary to form a robust long-term exposure-response relationship for UAM vehicle noise. The Airport Cooperative Research Program (ACRP) report [226] that preceded the NES indicated that individual studies often report contradictory findings, necessitating the need to average results across many studies. Surveys may be conducted by national authorities, local governments, academic institutions, or private organizations. Consistent, scientifically valid methodologies among multiple surveys will provide greater confidence in long-term exposure-response relationships and facilitate subsequent meta-analyses. Pilot studies are useful to test survey methods and tools before a final study is conducted. A mechanism such as a guidance document for the design and execution of UAM vehicle noise community surveys would increase the likelihood of the surveys being consistent and scientifically valid. Further, as community surveys are conducted, lessons learned should be documented and disseminated. The development of avenues for community noise surveys and lessons learned is the basis for recommendation SG3-2025-R5.

**Community Noise Survey Reassessment**

Reassessment of prior UAM community noise survey findings may be required as UAM vehicle operations change within communities. A first UAM community noise survey may be conducted with UAM vehicle operations that may be more limited than those that occur at some later time. Flight volumes, corridors (concentration and volume ranges), and aircraft designs can evolve. As UAM vehicle operations transition from infrequent to frequent, noise exposure patterns may differ from initial projections. Public attitudes toward UAM vehicle noise may shift with increased noise exposure, either through greater acceptance or heightened concerns. Initial community noise surveys provide a baseline, but a reassessment will give greater confidence that exposure-response relationships reflect real-world conditions and can inform policy and planning decisions.

To implement a reassessment strategy, the following should be considered:

- Focus laboratory and community noise surveys on changes that have occurred regarding UAM aircraft, operations, vertiport locations, other aviation noise sources, contextual factors, and ambient sound conditions.
- Refinements/updates to noise modeling tools and prior data generated from those tools based on new information on UAM vehicle noise in communities.
- Detection of evolving annoyance thresholds from comparative exposure-response analyses.

A determination should be made as to whether a UAM vehicle noise survey for a community should be repeated periodically, such as when a defined set of changes occur in the community that may affect UAM vehicle noise perception, such as a rerouting of UAM vehicle flights over the community.

#### 4.3.2.2 Exposure-Related Considerations for Community Noise Surveys

Quantification of community noise exposure requires predictive analyses, possible noise measurements/monitoring, and exposure metrics selection.

**Predictive Analyses and Collecting Noise Data**

Predictive analyses are typically used to quantify/estimate noise exposure. These require both computational tools and the data required to support analyses. The current practice for acquiring data through acoustic flight measurements is provided in Section 3.2 and gaps in Section 3.3. The current practices for community noise modeling and monitoring are provided in Section 5.2.2.3 and gaps in Section 5.3.2.5.

Items to consider for predictive analyses and data collection include:

- Tools:
    - For noise exposure estimation, use of internationally recommended integrated noise modeling methods, e.g., [227] or time-marching simulation tools, e.g., [123].
    - Tool readiness for quantifying UAM vehicle noise exposure. Are tools validated or is further tool development needed?
- Noise data:
    - Are necessary noise data available; e.g., noise-power-distance data for integrated modeling and source noise hemispheres for time-marching simulation?
- Operations data:
    - Are operations data including routes and trajectories, aircraft operational conditions, time structures, etc., available for noise exposure estimates?
- Noise measurements and monitoring:
    - As in the NASA Quesst mission, methods for estimating UAM vehicle noise exposure may require a combination of predictive analyses, field measurements in the surveyed community, and noise monitoring.

**Exposure Metrics**

The traditional long-term noise exposure metrics, $L_{dn}$ and $L_{Aeq}$ have been widely used for regulatory noise assessments, including airport noise compatibility planning studies under 14 CFR Part 150. Studies have noted the importance of re-evaluating current long-term noise exposure metrics [228,229]. Other metrics may support exposure-response relationships that complement, or that may provide, a more accurate representation of UAM vehicle noise community response than those based on $L_{dn}$ or $L_{Aeq}$. One consideration for UAM vehicle noise exposure metrics is that they may initially need to describe community response to a new noise source, which is an issue that is not faced when developing commercial aircraft noise metrics for areas around long-existing airports. The adoption of any alternative exposure metric must be based on its utility for estimating response as measured in community noise survey(s).

Characteristics of alternative long-term noise exposure metrics to consider include:

- Accounting for temporal variation in UAM vehicle noise events, which may be different from that of conventional aviation noise in terms of time structure, duration, and contributions from multiple vertiports.
- Evidence-based weighting for number and time structure of UAM vehicle events (see Section 4.3.1.3) or for the number of events that exceed a particular $L_{Amax}$.
- Metrics that account for UAM vehicle noise being masked partially, fully, or not at all by ambient sounds.

- Consistent temporal weighting (e.g., nighttime penalties or time-period-specific analyses) across metrics to enable valid comparison of metric performance.

Some potential alternative long-term UAM vehicle noise exposure metrics to consider are:

- $L_{dn}$ adjusted to capture some of the above characteristics of alternative long-term noise exposure metrics.
- NANL: Counts the number of events exceeding a given noise threshold rather than averaging sound energy.
- TAL: Measures the cumulative time that noise exceeds a set threshold.
- Peak Noise Metrics: Captures individual peak events rather than averaging them.
- Peak-day: While not a noise metric, peak-day, like annual-average-day (AAD), reflects the time duration over which a metric is calculated, with peak-day being the day with the most or the loudest noise events.
- Average busy day (ABD): A day whose operations are at least 50% of AAD operations.

#### 4.3.2.3 Response-Related Considerations for Community Noise Surveys

Quantification of the community response requires appropriate analysis methods and tools, survey methods, and metrics selection.

**Analysis Methods and Tools**

Methods and tools are needed for:

- Consideration of response differences across UAM vehicle configurations:
    - Responses to different UAM aircraft types may vary. Can the responses be generalized to allow a simple representation of human response to UAM vehicle noise?
- Consideration of response differences between UAM vehicles and other aviation noise sources, including other new entrants like sUAS.
- Development of a statistical exposure-response modeling framework:
    - A framework is needed to create an exposure-response relationship after data are collected. Models used in the NES and X-59 (e.g., multilevel logistic regression) may be applicable to UAM vehicle noise in addition to other models.
- Meta-analyses to combine results from different surveys.

**Survey Methods**

Survey methods encompass statistical methodologies to collect human response data in a community noise study. The study type determines whether a single or multiple surveys are conducted. The survey mode is how the response data are collected, and the survey questions determine which response data are to be collected. Sampling covers who and where data are collected and influences how they are to be combined.

- Study Type:
    - Cross-sectional or longitudinal. A cross-sectional study refers to a single survey of a population at a snapshot in time, whereas a longitudinal (or panel) study involves multiple surveys of the same population over time.
- Survey Mode:
    - Protocols for survey distribution (e.g., internet-based, paper survey, phone-based); consider influence of survey protocol on respondent demographics (e.g., survey protocol that may require sophisticated information technology skills).
    - How surveys will be introduced to participants. For example, to avoid influencing responses, community noise surveys may be introduced as surveys of general neighborhood satisfaction with some questions not being about noise.

- Sampling:
  - Establish minimum sample sizes to ensure statistical validity and power.
  - Sampling methods to achieve desired level of demographic representation among survey participants (e.g., probabilistic sampling based on postal addresses, convenience sampling).
  - Check sample for balance across key demographic variables.
- Survey Questions:
  - Recommended survey questions used for perception studies [197,230] while capturing UAM-specific concerns, including questions about the number of events, timing patterns, and operational predictability.
  - Consideration of respondent feedback with use of open-ended questions or questions with qualitative response choices.

**Response Metrics**

The baseline human response metric in community noise surveys is annoyance in terms of percentage highly annoyed (%HA). Additional human response metrics may be considered, including, but not limited to:

- Audibility (detection and noticeability): Use of annoyance and detectability models to estimate noise response that may use perception/sound quality metrics. Ambient sound data are needed to assess audibility and the effects of ambient sounds on annoyance (in addition to survey siting, Section 4.3.2.1).
- Acceptability: Before "acceptability" can be considered a useful metric, researchers need to define this term in relationship to UAM vehicle operations and development methods for its reliable and accurate measurement.
- Percentage highly sleep disturbed (%HSD) [231].
- Noise sensitivity: While also not a noise metric, it is a non-acoustical factor based on community expectations of noise and to which contextual factors contribute.

## 4.4 Recommendations

### 4.4.1 2020 Recommendations

Further development of metrics and validated predictive models of human response is needed to inform decision-making by UAM vehicle manufacturers and regulators. Specifically:

SG3-2020-R1. Measured and simulated vehicle acoustic data are needed to support subjective response studies for metric and predictive model development. It is recommended that efforts be made to acquire/generate such data (inclusive of metadata, e.g., vehicle location with respect to the receiver), and to make those data available for research purposes. **[Closed]**

SG3-2020-R2. Standardized processes for measuring and cataloging ambient noise are needed to facilitate its use in human subject testing. It is recommended that these processes be developed, inclusive of metadata documenting location, time of day, measurement equipment, etc. **[Closed]**

SG3-2020-R3. Community noise studies of early entrants are needed to assess the effectiveness of $L_{Aeq}$-based metrics as predictors of annoyance to long-term UAM vehicle noise. That may not be possible for some time. In the interim, it is recommended that laboratory studies be performed to help inform how different the annoyance to short-term exposure of UAM vehicle noise is from that of existing aircraft noise sources. Assessments can then be made to determine the sensitivity of noise exposure estimates to changes in the metric or to its level. **[Closed]**

SG3-2020-R4. Validated models for audibility, noticeability, and annoyance to UAM aircraft noise are needed to assess their utility for assessing community noise impact. It is recommended that such models be developed and validated over a wide range of operating conditions and demand scenarios, taking into account a representative range of ambient/background conditions. **[Progress Made]** [validation **Open**]

SG3-2020-R5. The assumption that airport noise of 65 dBA $L_{dn}$ is compatible with residential land use is based on a target of 45 dBA $L_{dn}$ inside the residence. It is recommended that transmission of UAM noise through residential (and commercial structures) be quantified in order to evaluate the 20 dB loss assumed by current land use compatibility guidelines. **[Open]**

SG3-2020-R6. It is recommended that measures of human response be developed and used as constraints in perception-influenced design. Ideally, such measures would be easily calculated and include sensitivities. **[Progress Made]**

SG3-2020-R7. Communicating community noise impact using integrated metrics, specifically $L_{dn}$, is often difficult because the metric bears little relation to how individuals experience noise. According to the recent Federal Interagency Committee on Aviation Noise (FICAN) research review [232] of aviation noise issues, supplemental metrics are those that supplement $L_{dn}$ in "communicating effects as opposed to supplementing $L_{dn}$ in assessing significance in the context of impact analysis." It is recommended that a comprehensive evaluation of supplemental metrics be performed in terms of their effectiveness and readiness for communicating the effects of UAM vehicle noise. **[Open]**

SG3-2020-R8. It is likely that different communities may react differently to the introduction of UAM vehicle noise, e.g., those communities that are regularly exposed to aircraft noise versus those that are not. It is recommended that a laboratory test campaign be used to explore differences in perception of UAM vehicle noise between communities, e.g., a round-robin test, so that future policy decisions are based on data representing a wide range of environments. **[Closed]**

Realigned from Section 2.4 [1] –

SG1-2020-R4. Auralization of UAM vehicle noise is important for understanding human response and communicating noise impact, especially in the absence of flight recordings. However, auralization tools that account for source unsteadiness (known to influence the perception of sound) are not well developed. It is recommended that continued development of auralization tools be performed to allow realization of flight operations (including takeoff, forward flight, landing, and transition) for a representative range of vehicle configurations. **[Closed – superseded by SG3-2025-R4]**

### 4.4.2 2025 Recommendations

Efforts should continue, in the form of short-term and long-term noise testing, to improve understanding of UAM vehicle noise response and to provide data that establish long-term UAM vehicle noise exposure-response relationships. It is recommended that:

SG3-2025-R1. Community noise surveys should be conducted to support the development of long-term exposure-response relationships that can help inform policy. Evaluation of multiple metrics, in addition to those currently used for noise exposure ($L_{dn}$) and response (%HA), should be considered as part of that effort. In this evaluation, consideration should be given to application of temporal weighting (e.g., nighttime penalties or time-period-specific analyses) consistently across metrics to enable valid comparison of metric performance. (Note: This aligns with recommendations 4.1 and 4.3 in the AAM National Strategy [8]).

SG3-2025-R2. Assessments be made of the efficacy of objective parameters to describe the annoyance response to single-event UAM vehicle sounds. These objective parameters include, but are not limited to, conventional noise metrics, perception metrics, operational procedures, and persistent factors in communities that may affect noise perception. Objective parameters also include those that predict the efficacy of long-term noise exposure metrics considered for community noise surveys. A framework for communicating the situations and context in which each objective parameter describes the annoyance response needs to be formed. (Note: This aligns with recommendations 4.3 and 7.7 in the AAM National Strategy).

SG3-2025-R3. Annoyance models be developed that can be applied to real-world conditions with complicated numbers and time structures of UAM vehicle flyover occurrences, beyond models that only relate annoyance to a summation of the mean-square pressures over all events. Demonstrate whether the addition of these models to contemporary metrics produces statistically significant improvements in the accuracy of noise annoyance prediction for multiple plausible UAM vehicle fleet noise scenarios that reflect diverse operational and community contexts. (Note: This aligns with recommendations 4.3 and 7.7 in the AAM National Strategy).

SG3-2025-R4. Continued development, updates, and validation of auralization tools be performed that account for source unsteadiness, transitional flight, prominent noise sources, and urban environment propagation and, if the auralization tools use machine learning algorithms, that the trade-offs of the algorithms and limitations/sufficiency and cost of training data be communicated. This recommendation allows the realization of flight operations (including takeoff, cruise, and landing) for a representative range of vehicle configurations and operating environments. (Note: This aligns with recommendations 4.1, 4.3 and 7.7 in the AAM National Strategy).

SG3-2025-R5. Mechanisms be developed, such as a guidance document or expert panels, to provide guidance for consistent and scientifically valid methodologies for UAM vehicle noise community surveys, including a means of documenting lessons learned and guidance on reassessing results. (Note: This aligns with recommendations 4.1, 4.2, 4.3 and 7.4 in the AAM National Strategy).

# 5 Regulation and Policy

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## 5.1 Introduction

A wide range of stakeholders may be involved in managing UAM noise – some of whom may have limited experience with noise-related issues. These stakeholders include manufacturers, operators, service providers, regulators, and policymakers at international, national, state, and local levels, as well as communities in urban, suburban, and even rural areas.

To support the integration of UAM and improve existing transportation systems, regulations and policies must evolve in parallel with technology and operations. This section provides an overview of current practices, identifies gaps, and offers recommendations to enable informed, coordinated decision-making. Each subsection addresses three main areas: noise certification, operational noise, and community engagement.

Noise Certification – The primary means of controlling aircraft noise at the source is through noise certification requirements. Noise certification ensures aircraft designs incorporate the latest airworthiness-approved noise reduction technologies, demonstrated through procedures relevant to daily operations, with standards based on technical feasibility, economic reasonableness, and environmental benefits.

Operational Noise – The sound generated by UAM vehicles during all phases of operation, including start up, takeoff and landing, including vertical takeoff and landing for VTOL-capable UAM, hovering, flight mode transition, and shutdown. See Section 2.1.1 for additional details. The FAA does not regulate operational noise from aircraft.

Community Engagement – Community engagement informs and involves the public, engages with communities, and meaningfully considers community concerns and views as regulators and operators make aviation decisions.

A key distinction for UAM is where vertiports are located, at airports or at non-airport sites, as this directly affects both operational noise exposure and how communities are engaged. Vertiport siting determines which jurisdiction has oversight, which in turn can result in different policies, decision-making processes, and community engagement practices.

## 5.2 Current Practice

This subsection addresses the current practice associated with noise certification, operational noise, and community engagement.

### 5.2.1 Noise Certification

This subsection describes noise certification standards from a global perspective, including from the ICAO, FAA, and individual national aviation authorities from the EU, Japan, and Brazil. The purpose of this subsection is to highlight the existing overlap between regulatory processes as well as identify nuances in individual approaches to AAM noise required by regional necessities.

Portions of this subsection address the AAM National Strategy [8] recommendation 7.4, "Demonstrate global leadership in advanced aviation by removing regulatory barriers and adapting economic policies to secure investments, partnerships, and security assurances needed for a strong U.S. aviation industry."

#### 5.2.1.1 International Noise Certification Standards

The ICAO is a specialized United Nations agency that works with Member States and aviation stakeholders to reach consensus on international civil aviation SARPs and policies in support of a safe, efficient, secure, economically sustainable and environmentally responsible civil aviation sector. These SARPs and policies are used by the ICAO Member States to ensure that their local civil aviation operations and regulations conform to global norms. CAEP is a technical committee of the ICAO Council focused on creating environmental SARPs and guidance. CAEP members are typically nominated by either the member states of ICAO or by ICAO Observer organizations, such as industry groups. Those organizations nominate subject matter experts to participate in CAEP working groups. ICAO CAEP Working Group 1 – Noise (WG-1) is the forum for technical aviation noise-related work. WG-1 plays a key role in developing and harmonizing noise certification standards in ICAO Annex 16 Volume 1 [7] and the associated ICAO Environmental Technical Manual (ETM) [233], which provides technical guidance on implementing the noise certification standards found in Annex 16 Volume I.

ICAO Annex 16 Volume I includes noise-related SARPs for airplanes, helicopters, and tiltrotors of conventional designs. These aircraft are configured with fixed wings, fixed rotors, or tilting proprotors to provide lift. Primary flight controls employ movable control surfaces for fixed-wing aircraft and rotor orientation changes for rotorcraft (a combination of the two schemes is used for tiltrotors). Noise levels at takeoff are primarily dependent on mass and power of the aircraft. Noise levels generally increase as aircraft weight and thrust are increased for a given technology level. Fixed-wing noise levels during approach are often influenced by airframe noise sources that are sensitive to the aircraft speed and configurations, in contrast to rotorcraft noise levels typically dominated by the high-amplitude BVI source during approach that tends to exceed airframe noise.

While some Member States may adopt ICAO noise standards directly, many states incorporate them into their own state-specific noise regulations. In the U.S., 14 CFR Part 36 [113] adopted the ICAO noise standards with additional provisions to meet national statutory requirements for aircraft noise control. This regulation is considered as harmonized with ICAO standards, and the noise limits in 14 CFR Part 36 are identical to those in the ICAO noise standards.

Current noise certification categories are based on aircraft design types, propulsion systems, and weight. However, these categories do not cover all aircraft designs. Some special-purpose aircraft may be excepted from noise certification requirements, for example aircraft designed and used for agricultural and firefighting activities. Depending on the authorities, experimental aircraft, military aircraft, and certain small general aviation aircraft may not be required to undergo noise certification.

UAM provides a new form of air transportation. UAM vehicles must be certified for airworthiness and thus for noise as well. For their noise certification basis, some UAM designs may be evaluated under the existing noise standards for helicopters or tiltrotors. However, other UAM designs may require modification of those noise standards or the creation of new noise standards.

UAM and sUAS, collectively, are referred to as Emerging Technology Aircraft (ETA) by WG-1. WG-1 maintains a task dedicated to development of noise standards for ETA. In the CAEP-13 cycle (ending in early 2025), WG-1 activities focused on collecting and sharing ETA noise data, understanding ETA noise characteristics, and discussions of noise measurement practices. Those activities continue in the current CAEP-14 cycle (2025-2028) with a goal of developing the first ICAO Annex 16 noise standards for ETA. As ETA designs continue to merge and mature, and as authorities continue to develop noise requirements for these vehicles, there is a broad consensus that noise standards should be globally harmonized whenever possible.

In addition to technical feasibility, the emerging noise standards may also need to assess cost effectiveness to balance the cost of a proposed standard against the environmental benefit.

### 5.2.1.2 Noise Certification Regulations in the United States

In the U.S., the FAA is the authority overseeing ETA operations, including airspace integration and safety. When an ETA applicant seeks an aircraft type certification (TC), the FAA establishes the noise certification basis for the model. This process typically involves several steps. First, the FAA conducts technical familiarization sessions to understand the aircraft design and performance characteristics, concept of operations, and mission flight profiles. Based on this understanding, the FAA then decides whether the aircraft design and its operational characteristics can be accommodated within the existing noise measurement procedures and whether the current noise standards (found in 14 CFR Part 36) can serve as the certification basis.

To support this decision, applicants may submit a white paper to the FAA that highlights the aircraft's design features and provides suggestions on noise standard selection or modifications of noise measurement procedures, along with supporting data and analysis. If the FAA concludes that the current noise standards cannot accommodate the potentially innovative design and operating characteristics of the ETA, it develops a Rule of Particular Applicability (RPA) for that aircraft model and modifies the appropriate current noise standards to fit the unique design. Serving as the interim standards before ETA noise standards are developed in 14 CFR Part 36, this RPA process has been published for seven UAS models and can be applied to UAM models as well. As of this writing, no UAM OEM has completed the RPA process, although several are working with the FAA on this.

To support the noise certification of ETA models and to support evaluation of ETA noise and its mitigation, the FAA conducts ETA noise research in collaboration with NASA, the U.S. DOT Volpe Center, and other organizations. For example, the FAA and the Volpe Center conducted noise measurement campaigns to gather noise data on multirotor and fixed-wing UAS vehicles. Through the FAA Center of Excellence for Alternative Jet Fuels and Environment (ASCENT) [234], the FAA and its partners support university-led research projects focused on understanding, quantifying, and predicting ETA noise via numerical modeling, laboratory test, and field flight measurements. As illustrated in this paper, research conducted at NASA – including laboratory studies, psychoacoustic investigations, numerical modeling, and field testing – has benefited diverse stakeholders by improving understanding of ETA noise and developing methods to quantify its impact.

FAA, NASA, and other U.S. institutions value the importance of developing internationally harmonized ETA noise standards and are actively engaged with the ICAO CAEP WG-1.

### 5.2.1.3 Noise Certification Regulations Outside the United States

The theme of the Spring 2025 UNWG meeting was the "International Regulatory Landscape." The following are drawn from presentations by three international regulatory agencies in addition to other publicly available information. Video recordings of the presentations are available on the NASA Langley Research Center YouTube channel [235]. Each agency is committed to participating in WG-1 in the development of dedicated SARP(s) for larger ETA, while promulgating interim noise requirements as needed.

**European Union**

EU Regulations 2019/947 and 2019/9453 set framework for the safe operation of civil UAS in the EU. They adopt a risk-based approach and define three categories of civil UAS operations: from one with no operating limitations ("open"), to one with operational authorization required from the national or local authority ("specific"), and to one with a requirement of air operator approval with type certification and a certificate of airworthiness ("certified"). The "certified" category is applicable to manned VTOL-capable aircraft. The EASA has published two EPTSs – one for VCA equipped with non-tilting rotors [114], and the other for VCA with tilting rotors [115]. The EPTS for VCA with non-tilting rotors was initiated from the measurement procedures of Chapter 8 of ICAO Annex 16, Volume I for large helicopters and mandates the same noise limits. Those procedures were adapted to account for the specificities of the designs considered. Similarly, the EPTS for VCA with tilting rotors is based on the measurement procedures of Chapter 13 of ICAO Annex 16, Volume I for tiltrotors with similar adaptations and with the same noise limits as for VCA with non-tilting rotors. Both EPTSs include supplemental hover noise testing for reporting purposes. They will be used to support the certification or validation of designs that have already applied to the EASA. The EASA further seeks to turn these EPTSs into European Commission (EC) regulations. An NPA was issued in August of 2025 [116].

**Japan**

The Japan Civil Aviation Bureau (JCAB) advanced air mobility rulemaking activities include the development of safety standards and regulations for aircraft, operations, etc., in cooperation with EASA and FAA. These were necessary to realize AAM operations at the 2025 Osaka-Kansai Expo. AAM vehicles are currently defined in Japan as either an "Aeroplane with VTOL capability" (vectored thrust, and lift and cruise) or a "Multi-rotor" (rotorcraft with more than 2 rotors). There have been four type certification applications since 2021, and the JCAB recently issued documentation describing the certification basis for the SkyDrive SD-05 multirotor vehicle, like the FAA Advisory Circular AC 21.17-4 for powered-lift. Existing noise standards for takeoff, overflight, and approach in Annex 16 Vol. 1, Chapters 8 and 13, will be used for type certification, and hover noise will be assessed with reference to procedures in the two EASA EPTSs.

**Brazil**

The Brazilian Agência Nacional de Aviação Civil (ANAC) follows its Regulamento Brasileiro de Aviação Civil (RBAC) 36 noise standards (adopted from 14 CFR Part 36) with adaptation of subparts H (helicopters) or K (tiltrotors) for application to eVTOL vehicles. The ANAC recognizes the need for standards that reflect eVTOL-specific characteristics, including hover noise (with the EASA EPTSs as a potential benchmark) and noise emissions that vary significantly with the flight phase. An interim approach includes the development of customized noise certification standards in consultation with the public.

#### 5.2.1.4 Industry Perspective on Noise Certification

One function of the International Coordinating Council of Aerospace Industries Associations (ICCAIA), representing manufacturers and service providers, is to provide input to the ICAO CAEP on issues related to aircraft noise through its Aircraft Noise and Emissions Committee. At the 2025 Spring UNWG meeting, the ICCAIA perspective addressed noise certification challenges including the need to manage the complexity of noise requirements in the development of noise standards regarding the proportionality of the requirement versus the environmental impact and societal benefit. The challenges also include the need for future requirements to have flexibility to fit different aircraft configurations and for harmonization of requirements to ensure a level playing field. It also identified challenges related to technical procedures in the evaluation of environmental impact and suggested several means for collaboration in the development of the ecosystem.

### 5.2.2 Operational Noise

This subsection examines the regulatory, governance, analytical, and operational frameworks that shape how UAM operational noise is evaluated and managed in the United States, including noise impact assessment and the National Environmental Policy Act (NEPA) implementation, vertiport siting and approval authority, community noise modeling and monitoring practices, and airspace integration considerations. As mentioned in the Introduction to this section, the methods of operating UAM aircraft also provide a potential pathway for noise reduction.

Portions of this subsection address the AAM National Strategy [8] recommendation 4.1, "Clearly communicate information and guidance on roles, responsibilities, and best practices for AAM planning to state, local, tribal, and territorial (SLTT) governments."

#### 5.2.2.1 Environmental Review Framework

**FAA NEPA Implementation**

The significance of noise impacts associated with UAM operations affecting residential and commercial structures in the United States is determined primarily through Federal regulations and land use compatibility policy. While noise experienced within the built environment is often subject to local noise ordinances, city and county noise ordinances do not apply to aircraft operations, and, as such, local governments generally lack regulatory authority to control aviation noise through local ordinance. However, local governments retain land use and siting authority, including decisions regarding whether and where vertiports for UAM operations are developed. This division of authority shapes how UAM noise impacts are evaluated and addressed under the Federal Aviation Administration's implementation of the NEPA. The FAA is not involved with local land use planning decisions when federal funding is not involved.

Effective July 3, 2025, the FAA issued Order 1050.1G [236], updating its procedures for implementing the NEPA and rescinding Order 1050.1F. The Order prescribes $L_{dn}$ as the primary noise metric and continues to use $L_{dn}$ 65 dBA as the threshold for determining significant noise impacts. An increase of 1.5 dBA or more in areas already at or above $L_{dn}$ 65 dBA is also considered a significant impact when compared to the no action alternative. The FAA adoption of $L_{dn}$ 65 dBA as the NEPA significance threshold is based on its designation as a level of aviation noise exposure considered incompatible with certain land uses, as reflected in the land use compatibility guidelines set forth in 14 CFR Part 150. The FAA does not regulate operational noise from aircraft, including UAM vehicles.

For the first time, the FAA formally incorporated AAM operations and vertiports located at federally obligated airports into its noise significance framework, outlining how these emerging technologies will be treated under the NEPA of 1969 [237]. The Order outlines how these emerging aviation technologies are to be evaluated under NEPA and clarifies that AAM operations are subject to the same $L_{dn}$-based significance thresholds that apply to conventional aircraft operations. As a result, $L_{dn}$, which has been widely used for regulatory noise assessments including airport Part 150 studies, is likely to continue to be applied in evaluating AAM noise exposure response relationships.

The contribution of eVTOL and other UAM noise operations to the existing $L_{dn}$ of a community may or may not be determined to be significant under the $L_{dn}$-based noise significance framework used by the FAA, depending on the noise characteristics of the aircraft, the number and time structure of operations, proximity to receivers, and ambient noise conditions.

If alternative metrics to $L_{dn}$ are found to offer advantages to describing UAM noise response, either in general or in specific circumstances, and they are not supported by AEDT, one potential challenge will be updating such tools so that these metrics may be used for decision-making. Note that AEDT already supports multiple metrics, including but not limited to the event-based metric NANL, which is currently used by the FAA as a supplemental metric. If metrics are not used for decision-making, they may be used for communication purposes as supplemental metrics after following established procedures for inclusion as supplemental metrics [236]. The FAA has issued procedures and measurement protocols for sound insulation programs funded through Federal grant assistance programs. The purpose of a Sound Insulation Program (SIP) is to develop a plan and approach for implementing sound insulation treatments to mitigate or minimize the effects of aircraft and airport-related noise on noise-sensitive structures located in high-exposure areas. Guidelines for the development and implementation of SIPs are provided in FAA Advisory Circular 150/5000-9B [238]. Under this framework, increased sound insulation may be considered as a mitigation measure for impacted structures when a significant increase in $L_{dn}$ exposure is identified.

The FAA National Aviation Research Plan 2025-2029 [239] notes that while some AAM vehicles may generate less noise than conventional aircraft, their unique operational profiles, including lower-altitude flight and closer proximity to people, introduce new challenges for noise assessment. Current certification methods may not apply, prompting the FAA to fund research on noise exposure near takeoff and landing sites and in affected communities [239].

**Categorical Exclusion Provisions**

The FAA conducts NEPA review under three levels: Categorical Exclusion (CATEX), Environmental Assessment (EA), and Environmental Impact Statement (EIS). CATEX involves the fewest procedural requirements and is used when no significant environmental impacts are expected. FAA Order 1050.1G includes several CATEX provisions that may be relevant to eVTOL operations. These are detailed in Table 3 (Appendix E.1).

**FAA Noise Policy Review**

The FAA released the analysis of the Neighborhood Environmental Survey (NES) in 2021 [204] to assess public response to aircraft noise near major U.S. airports (see Section 4.2.2.2 and Appendix D.2). The findings prompted the FAA to solicit comments from the public [240] and to subsequently initiate a Noise Policy Review (NPR) in 2023 to evaluate whether its current noise metric ($L_{dn}$) and significance threshold ($L_{dn}$ 65 dBA) remain appropriate given the updated understanding of community annoyance, potential health impacts, and the emergence of new entrants. This review confirms the commitment by the FAA to "develop policies that will assist all stakeholders with responsibility for addressing aviation noise," specifically including UAS, UAM, AAM, and other emerging technologies.

To support the NPR, the FAA Reauthorization Act of 2024 [3] requires the FAA to establish the Aircraft Noise Advisory Committee (ANAC) to incorporate stakeholder perspectives into future agency noise policy decisions. The ANAC was established in January 2025. As of this writing, the FAA has not issued a public solicitation for membership in the ANAC.

#### 5.2.2.2 Vertiport Siting and Governance

Portions of this subsection address the AAM National Strategy [8] recommendation 4.1.

**Federal vs. Local Oversight Implications**

The FAA's involvement in an airport or vertiport environmental review depends on whether or not the facility is federally obligated. At federally obligated airports or vertiports, meaning those either already included in the National Plan of Integrated Airport Systems (NPIAS) or otherwise receiving FAA funding with agreements to certain obligations and grand assurances, the project development is subject to FAA policies, airport sponsor obligations, and NEPA review. This means that these airport/vertiport projects would fall under the oversight by the FAA on the use of specific environmental assessment procedures and threshold for "significant impact."

In contrast, vertiports at non-federally obligated sites are not subject to FAA-led NEPA review. Instead, state or local jurisdictions take the lead on zoning, permitting, and land use review processes, which may impose restrictions on facility siting and on operations at initial approval or subsequently under applicable land use authority. These reviews may better reflect local context and community concerns but operate within a limited scope, noting that the FAA retains exclusive authority over airspace and the regulation of aircraft noise and operations. This means that while local jurisdictions can impose land use restrictions, including conditions on facility operations at initial approval such as hours of operation, number of operations, and permitted uses (e.g., passenger, cargo, emergency, or air tour activities), they cannot regulate the actual flight paths or dictate noise standards for aircraft in the airspace, because those fall under FAA purview. As an example, in 2025, New York City adopted restrictions on non-essential helicopter operations at city-owned heliports, including the elimination of sightseeing flights, while preserving other transportation-related flights, including airport access as well as medical, emergency, and governmental uses [241]. These restrictions are based on land use authority and are implemented through a local law governing the use of city-owned facilities. This action demonstrates that a city may define or modify allowable purposes and operational conditions for helicopter operations at existing facilities, and that the same land use authority could be applied to AAM operations at vertiports. Objections to the proposed bill are noted in a letter to New York City on behalf of the aviation community [242].

As shown in Table 4 (Appendix E.2), while local jurisdictions may define allowable uses and operating conditions at non-federally obligated sites, the FAA retains exclusive authority over airspace and flight paths.

### Siting and Environmental Review

At federally obligated airports or vertiports, FAA Order 1050.1G governs NEPA implementation. As discussed above, the Order now includes several possible provisions for CATEX, the lowest of the three levels of environmental review under NEPA, of UAM operations, though the FAA must still determine whether Extraordinary Circumstances exist, including the potential for significant noise or environmental effects.

At non-federally obligated sites, state or local authorities conduct environmental reviews under their land use and permitting authority. Details on noise analysis practices and considerations for these reviews are addressed in Sections 5.2.2.3, 5.2.3.3, and 5.2.3.4. An example of differing federal and local determinations occurred in College Station, Texas, where the FAA issued a Finding of No Significant Impact (FONSI) [243] for a drone delivery project (Phase 1 community noise assessment), yet the local community declined Phase 2 due to projected operation volumes.

### Vertiport Design Guidance and Uses

At federally obligated airports, vertiport layout and safety design must follow FAA guidance, including mandatory submission of Form 7480-1 (Notice for Construction, Alteration, Activation, Deactivation of Airports, under 14 CFR Part 157) to the FAA for review. At non-federally obligated sites such as rooftops or ground-based pads in urban areas, local or state land use authority applies if federal funding is not sought. Adoption of FAA design standards is not required, although a vertiport sponsor still generally submits Form 7480-1 to the FAA for review, especially when the project may affect airspace safety and integration with the National Airspace System (NAS). As of September 2025, the interim guidance from the FAA, Engineering Brief (EB) 105A [20], contains limited information on noise management. This may change when the FAA publishes future vertiport design guide documents.

### Operational Restrictions and Local Land Use

Federally obligated airports are subject to the Airport Noise and Capacity Act of 1990 (ANCA) and cannot impose local operational restrictions, such as curfews or flight limits, without FAA approval. At non-federally obligated sites, state or local jurisdictions can establish operational conditions during initial siting, permitting, or approval as part of their land use authority [244]. These may include limits on hours of operation, number of daily operations, or authorized use cases. Such conditions can only be set as part of the initial vertiport approval and must comply with applicable land use or zoning requirements.

### Vertiport Approval

New vertiport facilities at federally obligated airports undergo federal environmental review in accordance with FAA procedures, while, at non-federally obligated sites, state or local jurisdictions lead the review, using methods that can differ from federal practice. These methods may reflect the community's localized noise sensitivity. In best practice, they are conducted before site approval to inform decisions about siting, design, or operational limits (see Section 5.2.3.4, 5.3.2, and 5.3.3). Methods can include tools not typically used in current federal practice, such as counting the number of noise events above a prescribed level, i.e., NANL, locally defining operational forecasts and procedural scenarios, and analyzing the total impact for their community. Reviews may distinguish between UAM noise sources that are entirely new and those replacing existing aircraft, adjust thresholds of significance to guide decision-making, and establish requirements for early public notification and community engagement.

#### 5.2.2.3 Community Noise Modeling and Monitoring

The practice of estimating community noise exposure commonly serves two purposes. It serves to support land use planning in the vicinity of commercial airports and, in the United States, is required of federal agencies to assess the environmental effects of proposed actions prior to making decisions under the NEPA.

Noise exposure estimates may be made through noise monitoring, i.e., noise measurements made in the vicinity of air vehicle operations, or by noise modeling, i.e., computational tools using various modeling approaches. According to FAA Order 1050.1G [236], noise monitoring data are not required for FAA noise analyses but may optionally be included in a NEPA document. Further, noise monitoring data should not be used to calibrate the noise model, since acoustic data from noise monitoring systems may include non-aviation noise sources and are of unknown quality compared to the certification noise measurements, which are the source of the modeled data.

While federal policy applies to federally obligated airports and locations, local jurisdictions may still determine the need for modeling and monitoring approaches most appropriate to represent their community conditions.

**Community Noise Modeling**

There is currently no standardized or recommended method for estimating noise exposure due to UAM operations. There is, however, a recommended method for estimating noise exposure from airplanes in the vicinity of airports provided in ICAO Doc 9911 [227] (see also SAE 1845A [125] and ECAC Doc 29 [245]), which adopts an integrated noise modeling approach that is applicable only to fixed-wing aircraft. There is currently no recommended approach for estimating noise exposure using time-marching simulation methods. An overview of each modeling approach and the tools and databases required of each are summarized in Ref. [246].

NASA has largely addressed the 2020 recommendation to "more fully explore limitations in methods for assessing community noise impact of UAM vehicles in their operational environments" through a series of papers on the use of the FAA AEDT for modeling noise exposure due to UAM operations when modeled as fixed-wing aircraft [247,248] and as helicopters [249,250]. The AEDT computer program is compliant with ICAO Doc 9911 in fixed-wing mode and includes a helicopter mode capability derived from the legacy Heliport Noise Model (HNM) [251]. While other Doc 9911-compliant codes exist for fixed-wing operations, AEDT is the mandated tool for environmental modeling of commercial aircraft noise for FAA actions subject to NEPA and hence has been a focus of the NASA studies. A set of recommendations to the AEDT fixed-wing and helicopter modes for improved UAM noise exposure estimation [252] has resulted from these studies and the FAA has developed a draft plan for implementing those in AEDT helicopter mode, thereby closing recommendation SG1-2020-R7. AEDT version 4a [124] was recently released and contains improvements to the noise modeling of rotorcraft, which will also benefit the noise modeling of UAM vehicles.

NASA and others have also investigated the use of time-marching simulation methods for UAM noise exposure estimation, e.g., using the Volpe Advanced Acoustic Model [123] and the NASA ANOPP2 Mission Analysis Tool [87] in several recent studies [127,253,254]. As with integrated noise modeling, other time-marching simulation codes are available, e.g., EASA NORAH2 [255].

Some of the advantages of simulation methods over integrated noise modeling include the ability to more accurately model full source directivity and advanced propagation, e.g., in urban canyons, to the extent those may be needed. Only simulation methods can produce data for auralization of operations, and these data may be needed for some metric calculations (see Sections 4.2.1.1 and 4.3.1.5). However, it is widely recognized [227] that while simulation methods provide higher-fidelity noise exposure predictions than integrated methods, they come with the added burden of a more intensive noise data generation process (compared to that of noise-power-distance data used in integrated noise modeling) and are more computationally intensive.

**Community Noise Monitoring**

Noise monitoring systems are very common around large commercial airports globally. There are several standards and guidance documents available that help with the planning, operation, and distribution of the data for a monitoring system [256-259]. These noise monitors are commonly used for airport planning and informing surrounding communities about noise exposure levels. The noise monitoring data can also be used to inform and evaluate noise models and related analyses in planning or research contexts. This does not apply to regulatory AEDT use under NEPA, which operates under established FAA modeling protocols. While the standards are not specifically written to monitor the noise from UAM aircraft, there may be several parallels between the documents and the needs for noise monitoring around UAM vertiports.

A Noise and Operations Monitoring System (NOMS) is a technical tool used by airports for data and information gathering and is designed to meet a need at an airport to plan, monitor, and update noise abatement and other airport programs. A NOMS is a computer-controlled system used for recording and measuring noise, tracking flights, gathering weather data, and storing noise complaints and the response(s) of airport staff to those complaints. It uses a relational database that combines geographic information with ongoing noise and flight data acquisition. A NOMS includes many components, including a network of permanent and/or portable noise monitors that measure the noise environment around an airport, a system that receives data from FAA air traffic control radar systems or passive antennas that capture aircraft flight tracks, and other external data such as weather and radio voice recordings. All the collected data are stored in local computers and/or hosted by the NOMS vendor remotely or on cloud storage. Modern systems can be accessed from anywhere with internet access.

The data from a NOMS are generally utilized to facilitate the development and management of noise abatement programs at an airport. The data from a NOMS can also be used to support other airport functions such as planning, gate management, and accounting.

As UAMs operate both at the airport and outside the environs of the airport, the existing NOMS and commercial off-the-shelf acoustic monitoring instrumentation can be applied for the investigation and monitoring of UAM noise.

#### 5.2.2.4 Airspace Management

Commercial, general aviation, UAM, and UAS will increasingly share the NAS and may overfly the same communities. For people on the ground, the effect is not separated by aircraft type but experienced as layered noise, visual impacts, and perceived safety risks. The FAA’s UAMConOps Version 2.0 [12] illustrates this in Figure 4. New entrants are expected to operate in both corridors and non-corridor routes, adding complexity and noise at low altitudes. Overlapping activity already occurs between commercial flights and helicopters, including military operations, and future UAM and UAS operations may create similar intersections. Taken together, the ConOps example underscores two dimensions of complexity: cumulative noise and visual impacts on the overflown communities and the challenge to safely integrate all aircraft into the NAS.

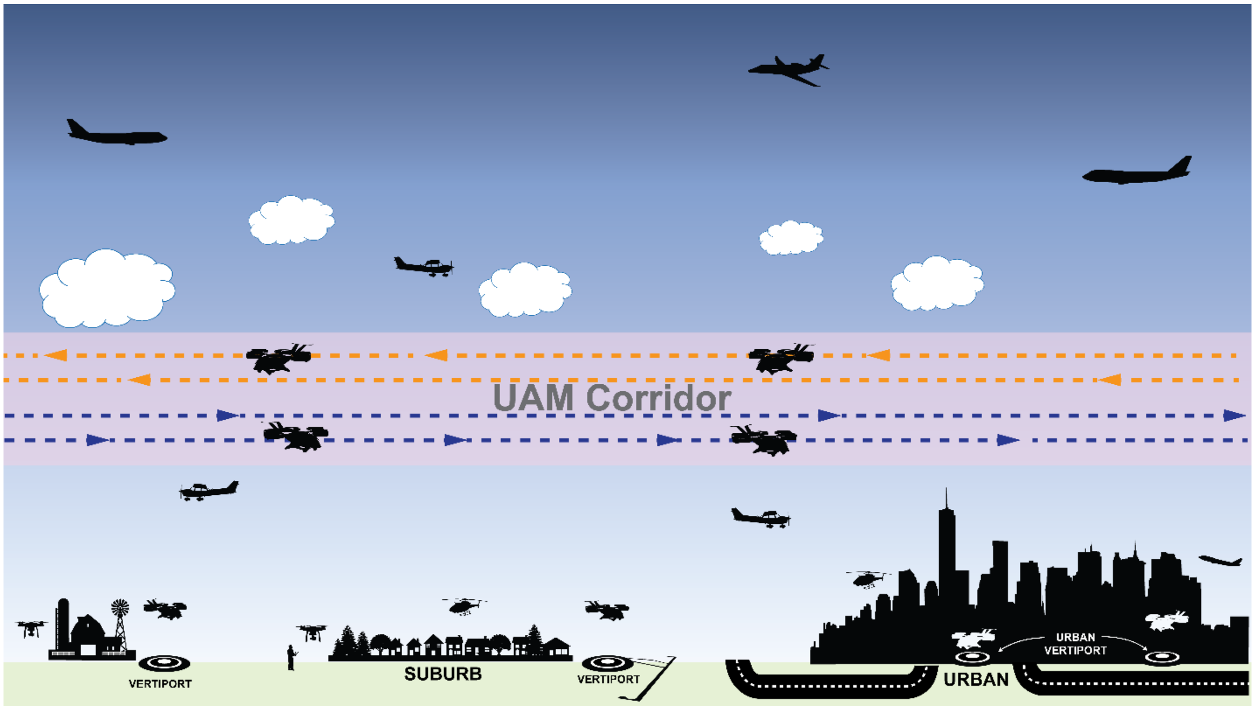

Figure 5: UAM corridor with multiple tracks (reproduced from Figure 7 [12]).

### 5.2.3 Community Engagement

A key element in integrating UAM into a community is early and proactive community engagement that builds trust and ensures community perspectives inform decisions. Effective community engagement provides the community with the information needed to understand the effects of UAM operations.

Community engagement is widely recognized as essential to the successful integration of UAM into future transportation systems [260]. The AAM Comprehensive Plan addresses the importance of collaborative research to understand the impacts of noise on a community and the associated community response [9]. The FAA states it is "committed to informing and involving the public and to giving meaningful consideration to community concerns and views as it makes aviation decisions that affect them" [261]. The agency further defines community involvement as "the process of engaging in dialogue and collaboration with communities affected by FAA actions," and notes that this process "supplements the public involvement activities required under other laws or requirements" [262].

The FAA recognizes that "public engagement and education through involvement of all stakeholders will be necessary to ensure that communities understand the benefits and effects of AAM operations, and to address any concerns they may have" [261]. It adds that for this emerging industry "to reach its fullest potential, it must gain the support of the general public," and "encourages communities to get involved now in these early phases, and to stay engaged" [261]. The FAA leverages its existing Community Involvement Manual (CIM) [261], which "provides flexible guidance and best practices applicable to all FAA actions," to inform its AAM/UAM public-engagement approach. The FAA may evolve its guidance over time in response to lessons learned. Meanwhile, the agency's Innovate28 implementation plan [262] is serving as the operational vehicle to test, demonstrate, and refine engagement approaches via pilot programs and partnerships.

Portions of this subsection address the AAM National Strategy [8] recommendations 4.2, "Develop and publish community involvement resources regarding AAM operations" and 4.3 "Research and develop tools to help communities, policymakers, and aircraft developers and operators evaluate noise impacts."

#### 5.2.3.1 Required or Optional Engagement

Community engagement under FAA-led NEPA is generally determined by the level of review: CATEXs do not require public notice or public involvement, while EAs and EISs may include formal notification and comment opportunities, see Table 5 (Appendix E.3). At sites without FAA funding, the scope and form of engagement may be shaped by state or local permitting and planning processes; in such cases, the FAA will coordinate with local authorities if requested and rely on the CIM as a guiding framework. For a fuller discussion of federal versus local oversight, see Section 5.2.2.2.

#### 5.2.3.2 Early and Proactive Engagement

Transportation and aviation agencies consistently emphasize the importance of initiating engagement early and maintaining a proactive approach throughout the planning process: "Start early and continue engagement into the long term" [263], "Undertake meaningful public involvement early in the planning process" [260], and "The community should be involved as early as possible. Early public input allows valuable information to be factored into project planning" [261]. Preparedness measures that support early and proactive engagement include updating land use provisions, developing outreach plans, clarifying jurisdiction/authority, ensuring permitting and review processes, and providing education for both local officials and the community. Despite these efforts, the timing of proactive engagement can be challenging, as local jurisdictions may need to make vertiport siting decisions including any conditions or restrictions before information is available on airspace corridors and procedures, operational volumes and noise levels, or use cases.

#### 5.2.3.3 Scope of Community Engagement Content

Multiple sources support the view that engagement should cover potential issues affecting the public and ensure they understand how proposed operations will affect them [260,262,264]. Innovate28 [262] calls for "tailored AAM information products for the general public and community groups," and the ACRP 2024 primer on AAM and community outreach emphasizes "what AAM will look like in the community rather than simply seeking public acceptance" [260]. Communities describe potential issues in terms of data that connect to how they would experience noise effects [225]. Engagement content can be framed around how people experience noise: number of events, time of day, audibility, cumulative exposure – not just aggregate, averaged metrics.

#### 5.2.3.4 Information Communities Need to Determine Impacts

Feedback from 4,857 public comments to the FAA NPR, as summarized in the Content Summary Report [265] by the FAA, underscores the need to fully inform communities of the effects of UAM operations. Comments identified factors such as number, timing, and loudness of events, cumulative aviation activity, and nighttime and low-altitude impacts (see Sections 5.3.2 and 5.3.3). The primer from the ACRP on AAM and Community Outreach [260] similarly emphasizes moving beyond seeking acceptance to fostering a shared understanding of how AAM will affect people where they live.

Experience from prior modernization of the NAS, particularly the Next Generation Air Transportation System (NextGen) initiative, reinforces these points. The Government Accountability Office (GAO) reported [266] that "Communities and some Members of Congress have raised concerns about FAA's implementation of NextGen and performance-based navigation (PBN), including whether the FAA provided timely and adequate information about potential noise effects to the public." The report observed that the "FAA initially lacked an understanding of how PBN implementation, and particularly the extent of flight path concentration caused by PBN, would affect communities in terms of noise because the changes in $L_{dn}$ as a result of PBN implementation were relatively small," and that the metric used to assess noise impacts "may not reveal changes in the number of flights in the sky above a given location." Like PBN, UAM is expected to concentrate routes and create high volumes of flights over specific communities.

According to GAO, "because DNL combines the effects of several components of noise into a single metric, it does not provide a clear picture of the flight activity or associated noise levels at a given location." The report noted that "100 flights per day can yield the same DNL as one flight per day at a higher decibel level, due to the averaging effect of FAA's metric." Because the description from the FAA of potential noise impacts is grounded in expected changes in $L_{dn}$, both in its environmental assessments and during its public outreach, communities may not fully understand the extent of changes to expect when being informed of a seemingly small change in $L_{dn}$. Because of this, there is a need for metrics that align with both decision-making and public perception. Regulators should employ and communicate both $L_{dn}$ and event-based metrics where practicable and clearly explain their different roles. See Section 4.3.1 for gaps in understanding metric efficacy to short-term noise and Section 4.3.2.2 for metrics to long-term noise exposure.

#### 5.2.3.5 Identifying Community Partners for Engagement

The NASA Considerations Playbook [267] identifies as a key challenge the need to "identify paths for providing information to members of the community, forums to solicit and listen to feedback, and avenues and opportunities for keeping them informed." In 2020, the FAA noted that it lacked a centralized group to facilitate information dissemination and collaborative problem-solving with communities [1].

The FAA announced the eVTOL Integration Pilot Program (eIPP) in September 2025. The program is meant to fast-track safe, scaled integration of eVTOL and other AAM aircraft into the U.S. NAS. It will be based on public-private partnerships (SLTT governments plus industry) proposing pilot projects to test operational concepts, aircraft designs, infrastructure, governance, safety, etc. These pilot sites should be used as two-way learning platforms: collecting community feedback, noise data, and operational insights, and then disseminating lessons broadly.

## 5.3 Gaps

### 5.3.1 Noise Certification

#### 5.3.1.1 Lack of data to inform noise certification

Developing noise certification standards for UAM aircraft is a challenge due to their unconventional designs, varied configurations and operations, and the limited applicability of existing regulations. Further, UAM technology is emerging and advancing at a very fast pace, adding to the challenges to develop noise certification standards to match the pace.

The first gap is associated with defining reference procedures. Current Part 36/ICAO Annex 16 procedures, designed for rotorcraft and tiltrotors, often do not fit with UAM use of automated control laws used in their distributed propulsion systems and flight profiles that potentially have significantly different energy management considerations. Updated or new procedures are needed to ensure that certification flight profiles are representative of real-world UAM operations and compatible with airworthiness requirements.

The second is that there is a lack of sufficient noise data to define appropriate reference conditions, develop noise–parameter functional relationships for correction to reference conditions, and characterize acoustic trends across different UAM designs. The data should, when possible, cover different flight modes such as hover, vertical-to-lateral flight transition, climb, and level flight. Comparable datasets are essential for establishing harmonized international noise standards, including noise limits.

The third is how to address UAM design diversity and taxonomy and applicability of noise standards. The range of UAM configurations complicates the creation of unified standards. A defensible acoustic taxonomy is needed to group aircraft with similar noise characteristics and to limit the number of certification standards. Both measured and simulated data may be needed to establish these groupings.

The fourth is how to further understand community response and noise metrics. Research to date showed evidence that UAS noise, although likely quieter in noise levels than that of conventional aircraft, may create heightened noise sensitivity in communities. While existing certification noise metrics appear suitable for provisional use, research into other noise metrics is needed to better manage community responses of UAM noise as well as to inform future noise standards.

### 5.3.2 Operational Noise

#### 5.3.2.1 Lack of Guidance for Vertiport Planning

While vertiport planning guidance documents have been released domestically [20] and internationally [268], there continues to be a gap regarding guidance for the compatibility planning of future UAM vertiports. During the 1980s, the Helicopter Association International (HAI) advised the FAA on voluntary guidance for the siting of new heliports. The FAA AC 150/5020-2 [269] resulted from this work, recommending suitable distances between a new heliport and its surrounding community based on a change in ambient noise level produced by operations. A revision was prepared in 1987 but was never adopted, and the 1983 AC was canceled in 1988.

Future UAM vertiport operations will vary between urban, regional, and rural locations, and while these aircraft are generally quieter than helicopters, noise consideration will still be needed. Guidance is needed on the identification of vertiport locations that would be compatible with existing or planned land use and on the assessment of environmental impact due to noise at proposed UAM vertiport locations. Additional existing regulatory or policy documents are summarized in Appendix E.3. Further federal guidance on vertiport siting and planning is anticipated.

#### 5.3.2.2 Unclear decision-making scope and authority

There is insufficient clarity on which operational restrictions, in addition to hours of operation, number of daily operations, authorized use cases or limits on the number of operations by use cases are permissible under local land use approvals and whether such conditions can be established after a vertiport site is approved.

#### 5.3.2.3 Incomplete representation of the lived experience for decision-making

Current practices, including datasets and metrics, as well as information and data provided for community engagement and local vertiport approval considerations, may not represent a lived experience of community members. As a result, there is a risk of creating roadblocks that delay or prevent UAM adoption. This gap can stem from noise representations and assumptions that misrepresent the lived experience in several ways, including the following examples. As noted in Section 1.3.2, UNWG participants did not reach consensus on the description of “lived experience.”

Noise representations may rely on ambient noise levels that substantially overstate actual community conditions (as shown by direct measurements of ambient noise levels) or presume that UAM operations will occur only in high-ambient noise environments. They may incorrectly generalize by presuming that UAM operations will replace existing helicopter operations rather than add a new source of noise, assuming that UAM vehicle noise will be masked by other sounds, or using modeling inputs such as altitude and noise levels that may not reflect actual events at specific locations. They may also misapply context-specific results (for example, the community response to emergency medical flights) to other use cases (such as frequent commercial air-taxi service). Community reaction to one context does not necessarily translate to another.

In addition, some UAM vehicle noise characteristics and the existing soundscape, i.e., the total sound environment for a specific community, may be overlooked. Psychoacoustic factors such as tone and pitch may also be discounted in current metrics. Community response to sUAS noise showing it can be more annoying than comparable levels of noise from legacy aircraft would suggest this is a concern that could also apply to UAM. While noise reductions at the vehicle source can reduce single-event sound levels under comparable operating conditions, community response to overflights is influenced by event-based exposure, including the count of events, routing concentration, altitude, and time of day, which should be considered. Service pricing projections may assume broad affordability, such as purported UAM pricing comparable to ride-hailing services, without providing clear assumptions or time frames for when such costs could, if ever, be realized. Finally, voluntary, non-enforceable noise-abatement procedures, which can sometimes help, have notable limitations: their compliance may vary by pilot and equipment; their use depends on conditions such as weather, time of day, traffic levels, and other safety considerations; and they may address only specific procedures so the relief they provide to communities could be partial, not comprehensive.

#### 5.3.2.4 Ambiguity in FAA definitions and interpretations under NEPA

Some FAA provisions, such as the CATEX for helicopter or eVTOL routes over "major thoroughfares" that "do not have the potential to significantly increase noise over noise-sensitive areas," use language that is sufficiently open to interpretation, creating uncertainty in how these terms are applied in practice and how they might be interpreted by the affected communities.

#### 5.3.2.5 Community Noise Modeling and Monitoring

**Noise Modeling**

Lack of a standard or recommended practice for modeling UAM noise exposure using either integrated noise modeling (akin to Doc 9911) or simulation approaches impedes consistent assessment of community noise effects for vertiport siting and land use planning, routing, and environmental impact as part of a cost-effectiveness analysis (see 5.2.1.1).

Specific to integrated noise modeling in AEDT helicopter mode [252] –

- Evidence suggests [250] that the fourth-power noise fraction model currently in use is only marginally applicable to AAM vehicles, and that differs between departure, overflight, and approach flight conditions. It may therefore be appropriate to make other power models available for use.
- The extrapolation used in the AEDT lateral directivity adjustment may not accurately reflect the noise at lateral receptors with azimuthal angles > 45°. This will be particularly important for AAM vehicles that fly at low altitudes because noise could be significant for larger azimuthal angles.
- Both maximum noise level and noise exposure NPD data should be provided to avoid approximation of the former using a relationship based on fixed-wing data.

Lack of a generalized UAM vehicle performance model for use with either the integrated noise modeling or the simulation approaches introduces a reliance on an external flight performance code to ensure that profile points are consistent with the performance characteristics of the aircraft. In lieu of that, automated methods for selection of operational modes from flight profile data would be beneficial to both integrated noise modeling and simulation.

There is a lack of publicly available UAM vehicle source noise hemispheres needed for simulation and noise-power-distance (NPD) data needed for integrated noise modeling. There are no standards for development of source noise hemispheres from flight test or predicted data; however, there is guidance [119] for flight test measurements needed to acquire needed data. SAE AIR-1845A is the applicable standard for generating NPD data from noise measurements of fixed-wing aircraft. However, it does not apply to rotary-wing aircraft including UAM vehicles. Despite the lack of a standard, NASA has generated publicly available fixed-wing and rotary-wing type NPD data using UAM vehicle source noise hemispheres generated by prediction that essentially follows the fixed-wing standard procedure [127].

There have been no studies performed to evaluate the trade between accuracy and capability (code and data), particularly regarding noise estimates near vertiports where changes in vehicle operation, e.g., transition from vertical to forward flight, can significantly change the noise produced.

**Noise Monitoring**

Adapting existing airport NOMS to reliably capture UAM operations requires an understanding of what updates are needed and how practical they are. Potential changes may include the following:

- **Core functions** such as sound pressure level measurement, frequency analysis, and temporal logging are transferable, but adaptations will be needed to capture unique spectral and temporal characteristics of UAM vehicles, including impulsive components and rapid fluctuations.
- **Standardization protocols** for sensor calibration, data acquisition, treatment of ambient sound, and validated analysis methods will be essential to ensure comparability across studies and build robust monitoring systems.
- **Operational scaling** may introduce additional concerns, including visual population exposure, privacy, and the need to integrate aircraft registration, tail numbers, and Mode-S transponder codes into monitoring databases.

For non-airport vertiports managed by local authorities, it remains uncertain whether cost-effective monitoring systems can provide sufficient information without extensive staffing or infrastructure.

### 5.3.3 Community Engagement

#### 5.3.3.1 Undefined criteria for timing, and responsibilities for early and proactive engagement

An objective way to determine whether engagement has occurred early and proactively in the planning process is missing. Clear project milestones or decision points, such as vertiport siting, corridor definition, or operational volume forecasts, for when engagement should begin are not defined. Minimum content requirements for what constitutes “meaningful engagement” are not consistently defined for AAM contexts: who should lead (FAA, local government, or operator), how content should be delivered, and how continued involvement is maintained are left ambiguous. Communities should not be left with the mistaken impression that the FAA is involved with local land use planning decisions (e.g., the siting of a UAM vertiport) when federal funding is not involved. The operators, local governments, and communities should work together on these land use planning decisions. Communities should also be aware that the FAA does not regulate operational noise from aircraft, including UAM vehicles.

#### 5.3.3.2 Incomplete or evolving information to support decision-making

Vertiports may be proposed before operational volumes, vehicle type, flight origins, airspace procedures, or corridor alignments are known. This creates a dilemma for local agencies: proceed with limited information or delay decision-making. If conditions cannot be modified after approval, jurisdictions must forecast a range of potential impact scenarios during initial siting, the only time when restrictions can be imposed and incorporate those forecasts into their decision-making criteria as well as clearly communicate the scope and implications of those restrictions to the public. The information conveyed to communities must align with the information used for decision-making. There should be no disconnect or incompatibility between what is explained publicly and what is used to make regulatory decisions; both must rely on the same or similar metric(s) to ensure transparency and community trust.

#### 5.3.3.3 Lack of mechanism for public input on potential unusual public controversy

For CATEX-level actions under FAA-led NEPA, there is currently no requirement to notify the public, release the Initial Environmental Review (IER), or engage the community (see Section 5.2.3.1). As a result, affected communities have limited opportunity to express concerns that might indicate unusual public controversy or raise Extraordinary Circumstances that could warrant a higher-level review. The FAA IER form includes a prompt that asks whether such concerns have been raised. However, because the IER itself is not public and no notice or engagement is required, the FAA may miss opportunities to fully identify potential controversy or Extraordinary Circumstances of which they may not be aware.

## 5.4 Recommendations

### 5.4.1 2020 Recommendations

It is recommended:

SG4-2020-R1. That at the national level, the FAA, in collaboration with other agencies and the industry, address certification, standards, and environmental reporting for UAM noise before these vehicles enter service. This is needed so that local communities are not panicked into the establishment of ordinances that will both limit growth of the market and potentially create operationally restricted zones. **[Progress Made]**

SG4-2020-R2. That i) Industries be more proactive in approaching regulators to help them understand vehicle designs, noise characteristics, operating modes, etc., and to share relevant data, and ii) Regulators help the industry to understand the regulation process and policies, and identify specific data needs to bridge gaps in standards and procedures. R&D programs, technical committees, and workshops are some of the venues that such collaborations can take place, in addition to direct communications. **[Progress Made]**

SG4-2020-R3. To collect more data in the field through R&D programs and to leverage data from manufacturers. The data would not only help to support noise certification of UAM vehicles, but also to assist the development and validation of noise prediction capability for noise impact analyses and to identify approaches and best practices for quiet aircraft designs and for quiet flight operations. **[Progress Made]**

SG4-2020-R4. That regulators and policy makers work to clarify the boundaries of responsibilities in managing UAM noise, and support development of guidance for vertiport planning regarding both location identification and environmental assessment at the proposed locations. **[Progress Made]**

SG4-2020-R5. To develop a strategy and framework for community engagement before UAM noise concerns arise. Being prepared to address local community noise concerns early in the process will be critical to success for this market. Initial flight operations should not come as a surprise to the affected community. Modern tools such as virtual reality with auralization could provide effective ways to inform and engage the public. **[Closed – superseded by SG4-2025-R1]**

Realigned from Section 2.4 [1] –

SG1-2020-R7. Tools like AEDT were developed to support mandated community noise assessments of aircraft operations near airports. The current lack of support specifically for UAM vehicles (e.g., performance models), requires analysts to accept the limitations associated with using existing capabilities (e.g., helicopter mode or fixed-point flight profiles in the fixed-wing mode). It is recommended that research be conducted to more fully explore limitations in methods for assessing community noise impact of UAM vehicles in their operational environments, and to generate a software development plan that addresses the limitations of current models over time. **[Closed]**

### 5.4.2 2025 Recommendations

It is recommended:

SG4-2025-R1. To develop an Implementation Guide to support early and proactive community engagement by adding specificity to existing frameworks. The guide would include elements such as usage scenarios with expected purpose distribution, forecasts of future demand, a noise effect template, standardized UAM vehicle-to-other aircraft comparison templates (e.g., one for helicopters, one for propeller aircraft), methods for evaluating total noise effects from the layered combination of all transportation types and facilities, criteria for early and proactive community engagement, airspace management (including but not limited to UAM corridor concentration, cruising altitudes, aircraft separation and other safety concerns, adjudication, and staffing for air traffic control), and key regulations and interpretations. To support this effort, a process should be established to identify, track, and obtain critical-path information that is not otherwise available, with responsibilities assigned. Without this level of detail and role clarity, UAM adoption risks delays in approvals and deployment, along with a loss of community trust. (Note: This aligns with recommendations 4.1 and 4.2 in the AAM National Strategy [8]).

SG4-2025-R2. That AAM pilot studies be used as two-way learning platforms: collecting noise data and operational insights and then disseminating lessons broadly. The FAA should maintain a centralized engagement hub, such as a public-facing portal, to coordinate outreach resources, data, and pilot updates. This helps reduce fragmentation, improve access, and foster transparency and trust. (Note: This aligns with recommendation 4.3 in the AAM National Strategy).

SG4-2025-R3. To establish a focused, multi-year expert task force and assign it to early implementations to ensure lessons learned are systematically captured and shared. This task force would perform stakeholder interviews, synthesize operating profiles, identify insights on noise certification, operational noise, and community engagement, capture findings on lived experience and applicable metric(s), and clarify barriers and uncertainties across all areas of focus. Periodic briefs for regulators, industry, and communities would provide a structured and continuous body of knowledge that complements the UNWG papers, supporting UAM adoption, building trust, informing future practices, regulations, policies, and the evolution of decision-making metric(s). (Note: This aligns with recommendation 4.2 in the AAM National Strategy).

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# Disclaimers

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# Appendix A List of Acronyms

| | |
|---|---|
| AAM | Advanced Air Mobility, also<br>Advanced Acoustic Model |
| AC | Advisory Circular |
| ACRP | Airport Cooperative Research Program |
| ADP | Group ADP, Paris Airports |
| AGL | Above Ground Level |
| AEDT | Aviation Environmental Design Tool |
| ANAC | Brazilian Agência Nacional de Aviação Civil, also<br>Aircraft Noise Advisory Committee |
| ANCA | Airport Noise and Capacity Act of 1990 |
| ANOPP2 | NASA 2nd Generation Aircraft Noise Prediction Program |
| BFI | King County International Airport – Boeing Field |
| BPF | Blade Pass Frequency |
| BPM | Brooks, Pope, and Marcolini |
| BVI | Blade-Vortex Interaction |
| BWI | Blade-Wake Interaction |
| CAEP | ICAO Committee on Aviation Environmental Protection |
| CATEX | Categorical Exclusion |
| CFD | Computational Fluid Dynamics |
| CFR | Code of Federal Regulations |
| CIM | Community Involvement Manual |
| ConOps | Concept of Operations |
| DEP | Distributed Electric Propulsion |
| DGAC | French Civil Aviation Authority (Direction Générale de l'Aviation Civile) |
| DNL | Day-Night Average Sound Level |
| DOT | United States Department of Transportation |
| EA | Environmental Assessment |
| EASA | European Union Aviation Safety Agency |
| EB | Engineering Brief |
| eC/STOL | Electric Conventional/Short Takeoff and Landing |
| eCTOL | Electric Conventional Takeoff and Landing |
| EEH | Equal Energy Hypothesis |
| EIS | Environmental Impact Statement |
| EPNL | Effective Perceived Noise Level |

| | |
|---|---|
| EPTS | Environmental Protection Technical Specifications |
| ETA | Emerging Technology Aircraft |
| EU | European Union |
| eVTOL | Electric Vertical Takeoff and Landing |
| F1A | Formulation 1A of Farassat |
| FAA | Federal Aviation Administration |
| FONSI | Finding of No Significant Impact |
| FWH | Ffowcs Williams and Hawkings |
| GAO | Government Accountability Office |
| ICAO | International Civil Aviation Organization |
| LES | Large Eddy Simulation |
| LTO | Landing and Takeoff |
| NANL | Number of Events Above a Threshold Noise Level |
| NAS | National Airspace System |
| NASA | National Aeronautics and Space Administration |
| NEPA | National Environmental Policy Act |
| NES | Neighborhood Environmental Survey |
| NOMS | Noise and Operations Monitoring System |
| NPA | Notice of Proposed Amendment |
| NPD | Noise-Power-Distance |
| NPIAS | National Plan of Integrated Airport Systems |
| NPR | Noise Policy Review |
| OEM | Original Equipment Manufacturer |
| RAM | Regional Air Mobility |
| RANS | Reynolds-Averaged Navier-Stokes |
| ROD | Record of Decision |
| SARP | Standards and Recommended Practice |
| sUAS | Small Unmanned Aircraft Systems |
| SEL | Sound Exposure Level |
| SLTT | State, Local, Tribal, and Territorial |
| STOL | Short Takeoff and Landing |
| TAL | Time Above a Threshold Noise Level |
| TDBEM | Time-Domain Boundary Element Methods |
| TIN | Turbulence Ingestion Noise |
| UAM | Urban Air Mobility |

| | |
|---|---|
| UAS | Unmanned Aircraft Systems |
| UNWG | UAM Noise Working Group |
| VCA | Vertical Take-off and Landing Capable Aircraft |
| VTOL | Vertical Takeoff and Landing |
| WG-1 | ICAO CAEP Working Group 1 – Noise |
| WPS | Wall Pressure Spectrum |

# Appendix B List of Symbols

| | |
|---|---|
| $L$ | Sound pressure level (dB) |
| $L_{Amax}$ | Maximum A-weighted sound pressure level (dBA) |
| $L_{AE}$ | A-weighted sound exposure level (dBA) |
| $L_{Aeq}$ | A-weighted equivalent continuous sound level (dBA) |
| $L_{den}$ | Community noise equivalent level (dBA) |
| $L_{dn}$ | Day-night average sound level (dBA) |

# Appendix C UAM Noise Working Group

## C.1 Working Group Activities

The Urban Air Mobility Noise Working Group (UNWG) holds semiannual meetings hosted by NASA Glenn Research Center and NASA Langley Research Center. The meetings have included focused presentations and panel discussions on perspectives on noise, noise in the vertiport environment, community engagement for advanced air mobility, and the international regulatory environment. Overviews on progress towards goals from the four subgroups (Tool Development and Experimental Validation, Ground and Flight Testing, Human Response and Metrics, and Regulation and Policy) are also presented. Over 200 individuals from over 20 countries attend the semiannual meetings, many of whom are actively engaged in the efforts of one or more of the subgroups. In addition to the semiannual meetings, the subgroups typically hold monthly meetings where the majority of the work is performed.

## C.2 Participating Organizations

The following represents a partial list of organizations registered for the semiannual UNWG meetings since 2023:

Acentech
Advanced Air Mobility Institute
Advanced Rotorcraft Technology
Aerospace Technology Institute
Airbus
Airbus Helicopters
Airport Regions Council
Amazon
Amentum
Analytical Mechanics Associates (AMA)
Analytical Services and Materials (AS&M)
ANT Automation
Applied Research Labs, UT Austin
Archer Aviation
ARIS Inc.
Ascendance
Arup
ATAC
ATA Engineering
Athule Aero Technologies
ATI
Aviation-Impacted Communities Alliance (AICA)
AVEC
Aurora Flight Sciences
Axiometrix Solutions
Baylor University
Bell Flight
Blue Halo
Blue Ridge Research and Consulting
Boeing
Booz Allen Hamilton
Boston University
Brazos Innovation Partners
Cleveland Hopkins International Airport
Confortus Acoustic Engineering
Continuum Dynamics
Cornerstone Research Group
Cranfield University
Crown Consulting
CSI
Dallas/Ft. Worth International Airport
Dassault Systemes SIMULIA
Design, Analysis and Research Corporation
Embraer
Embry-Riddle Aeronautical University
ESI Group
European Union Aviation Safety Agency (EASA)
Hottinger Brüel & Kjær
Eve Air Mobility
FAA Office of Environment and Energy
Federal University of Santa Catarina
Ferrovial Vertiports
Florida State University
French Aerospace Lab (ONERA)
French Civil Aviation Authority (DGAC)
Finnish Transport Agency Traficom
Flexcompute
GE Aerospace
Georgia Institute of Technology
German Aerospace Center (DLR)
GPG Enterprises
GPU-Prime
Great Lakes Sound & Vibration
Gulfstream Aerospace
Hanseo University
Hanwha Systems
Hexagon
Hexcel Corporation
Harris Miller Miller & Hanson (HMMH)
Honeywell
HX5
Interdisciplinary Consulting Corp. (IC2)

Japan Civil Aviation Bureau (JCAB)
Joby Aviation
John Wood Group PLC
Kent State University
Kobayasi Institute of Physical Research
Korea Aerospace University
Lilium
Lockheed Martin
Maglev Aero
Mainstream Engineering
Metron Aviation
Michigan Technological University
Milwaukee Tool
Mississippi State University
Morin Aeroacoustic Consulting
Munich Aeroacoustics
Nanyang Polytechnic
NASA (Ames, Glenn, and Langley Research Centers, and Armstrong Flight Research Center)
National Center for Physical Acoustics
National Civil Aviation Agency of Brazil (ANAC-Brazil)
National Institute of Aerospace
National Research Council Canada (NRC)
NC A&T State University
NLR (Royal Netherlands Aerospace Center)
North American Aerospace
North Carolina State University
Northrop Grumman Aeronautics Systems
Ohio Aerospace Institute
Ohio State University
Oklahoma State University
Old Dominion University
Oppenheimer Consulting
OptiNav
Optis Engineering
Owens Corning
Pennsylvania State University
Pipistrel Vertical Solutions
Politecnico di Milano
Politecnico di Torino
Porsche Engineering
Portal Aerospace
Predictive Acoustics
PSA3
Purdue University
Pusan National University
Queen Mary University of London
Rawlins Infra Consult
Rolls-Royce
Royal Military College
RTX (Collins Aerospace, Pratt & Whitney, Technology Research Center)
Scantek, Inc.
Siemens DISW
Sikorsky
Spirit AeroSystems
ST Engineering
Stanford University
SUBlime
Supernal
Techsburg
Textron Aviation
Transport Canada
TU Delft
TU Munich
Tuskegee University
U.K. Civil Aviation Authority (CAA)
University of Bristol
University of California Irvine
University of Cincinnati
University of Florida
University of Illinois Urbana-Champaign
University of Maryland
University of Michigan
University of Notre Dame
University of Salford
University of Sherbrooke
University of Southampton
University of Toledo
Unmanned Systems Bulgaria
U.S. Air Force (HAF, AFRL)
U.S. Army (DEVCOM ARL, DEVCOM AvMC)
U.S. DOT Volpe Center
U.S. National Park Service
U.S. Navy (NAWCAD, Naval Research Lab)
Utah State University
Vertical Aerospace
Virginia Tech
Whisper Aero
Wichita State University
Williams International
Wisk

# Appendix D Human Response and Testing

## D.1 VTOL Paris 2024 Project (4.2.2.1)

The VTOL Paris 2024 project was launched in 2020 by ADP (Paris Airports) with the objective of providing an experience of VTOL commercial flights above Paris city in 2024. In this effort, ADP was associated with Volocopter, both the provider of the Volocity eVTOL vehicle and the air flight company. The French Civil Aviation Authority (DGAC) was involved to support regulatory and oversight aspects. Among several operational objectives, the creation of a vertiport on the Seine River offered many lessons learned for different stakeholders.

For the project needs, five vertiports were implemented: four in existing airports (private areas already managed by ADP), and one in the center of the city. The choice of the location of this latter vertiport was based on existing helicopter routes, to avoid the complex process of creating new routes. On the route from the Paris-heliport to the hospital of "La Pitié-Salpêtrière," the Seine River at "Quai d'Austerlitz" was chosen for its proximity to existing public transports and for the limited number of residential buildings in the area. The creation of the vertiport involved two public consultative opinions to help the French Minister of Transports to sign the authorization: an EIS in 2023 and a public enquiry in late 2023.

The EIS is a public document that gathered the description of the project (objectives, duration, number of flights, etc.), the existing state of the area before the vertiport creation (landscape, noise, pollution, fauna, flora, etc.), and the impacts of the vertiport on this state and their mitigations. Regarding noise, as no measurements of the Volocity were available, the noise impact study was made using measurements of the VC-2X demonstrator, which is half the weight but has the same multirotor architecture as the Volocity vehicle. The EIS pointed out that the eVTOL noise should be lower than the ambient sound, wherever its location in the vertiport area and along the route, except very close to the vertiport. Indeed, the closest wall of a fashion school building is about 20 meters from the vertiport; complementary on-site measurements and analyses showed that the eVTOL noise should not be heard inside the building. The independent "Environmental Authority" considered the global impact study as incomplete, provided several recommendations, and gave a negative opinion. The main concern related to noise was the lack of noise exposure estimates for the population. Such estimates were not possible with the available tools. As planned in the process, ADP provided a report on this opinion with responses to each point raised. The opinion of the Environmental Authority was picked up by many press publications, with interviews of stakeholders.

A few months later, the public inquiry was launched online, in addition to several physical permanencies and a public meeting (about 200 participants). All the documents relating to the project were made available, including the conclusions of the impact study, the detailed opinion, and the response of the ADP. There were many contributions (more than 1700), including letters from politicians and associations. Approximately 87% expressed negative opinions and 10% positive opinions. Noise appeared to be the highest concern. As a result, the commissioner for the public inquiry also gave a negative opinion. Despite the negative opinions, the Minister of Transport signed the authorization to create the vertiport, which was ready in July 2024. Ultimately, no flights were operated due to delays in the development of the aircraft.

A lesson learned from the VTOL Paris 2024 project is that the negative community response to the online inquiry might have been reduced or mitigated with more effective community engagement prior to the inquiry. Most of the participants gave their opinion about eVTOL (or air taxi for most of them) as a whole and disregarded the fact that the project was an experiment with several objectives, noise measurements in operational conditions among them. Ironically, it is only the experiment itself that could have provided insight into the community experience and reaction to eVTOL noise.

## D.2 Contemporary Community Noise Surveys Relevant to UAM (4.2.2.2)

### Neighborhood Environmental Survey

The FAA conducted a nationwide survey, the NES, regarding annoyance related to aircraft noise [204]. Following the NES findings, the FAA issued a Request for Comment on its Noise Policy Review [240]. The FAA received 4,857 comments from across the U.S., and a summary of these comments is available online [265]. Key findings from that input include:

- $L_{dn}$ was the most frequently mentioned metric (959 mentions without a specific location), with approximately 95% of those comments **not** recommending its continued use.
- Support was noted for $L_{dn}$ close-in to airport communities but not for communities experiencing overflights.
- NANL was the most frequently recommended alternative metric (916 mentions), followed by the $L_{dn}$ and $L_{den}$ metrics (approximately 650 mentions each) for close-in to airport communities.

These findings reflect a growing public interest in how noise is measured and perceived and suggest a preference among some for metrics that better capture the lived community experience, particularly event- and time-based metrics such as NANL and TAL.

Regarding the NES study itself, while the NES was not intended to include communities exposed to aircraft $L_{dn}$ levels below 50 dBA, a study by Brenner and Hansman [228] indicated that annoyance can occur when $L_{dn}$ is below 50 dBA. To develop a national exposure-response curve, the NES primarily focused on individual airports and did not account for communities exposed to overlapping traffic from multiple airports, which is applicable to some communities. The one case of overlapping traffic included in the NES was King County International Airport - Boeing Field (BFI) and Seattle-Tacoma International Airport (SEA). BFI respondents were exposed to flights from both BFI and SEA, and they had a combined $L_{dn}$ value. In the NES, there may be areas where respondents were exposed to traffic from multiple airports (e.g., New York City, Los Angeles, Chicago) but not calculated in their $L_{dn}$. Overlapping airport traffic in these areas was not considered in the NES because, other than SEA/BFI, the 50 dBA $L_{dn}$ contours at the remaining 19 airports did not overlap with other airports in the sample.

### Quesst

The NASA Quesst mission [205] is planning to gather exposure-response data to inform regulators in their efforts to potentially develop noise standards for overland supersonic flight. NASA and Lockheed Martin developed a low-boom flight demonstrator aircraft, X-59, to use in a series of staged community tests.

The Quesst mission will evaluate both single-event and cumulative survey responses, with a greater focus on single events. Annoyance ratings will be collected using a web-based survey instrument and evaluated on a five-point verbal scale [197]. Noise exposures are estimated for each flyover event via a combination of ground-based field measurements and physics-based predictions. Community noise surveys are planned at up to five sites across different geographic locations, to increase representativeness, with at least 1000 participants per site. Because both Quesst and future UAM community noise surveys will estimate community noise exposure and assess noise annoyance, some tools and methods developed for the Quesst mission may also apply to future UAM community surveys. For example, analysis tools, such as exposure-response statistical models, may be useful for determining UAM exposure-response relationships.

In 2018, a community noise survey was conducted over a two-week period in Galveston, Texas, using a NASA research aircraft flying a supersonic dive maneuver to simulate a low-boom acoustic waveform [270-272]. The survey showed that NASA could successfully engage with a community to conduct a community noise survey. The lessons learned included early community engagement, with separate communications plans for local air traffic control, elected officials, the general public, and survey participants. In terms of the survey, reminder messages sent to survey participants helped improve survey completion rates. In terms of noise exposure, acoustic measurements were affected by ambient sound. For all data collected, the need for automation in data reduction and analysis was identified, especially if multiple community tests are planned within a calendar year.

In 2023, a multiple-week survey method test was completed with members of the public in Nashville, Tennessee [273]. Because there were no flyovers by X-59 or other supersonic aircraft, respondents were asked about their reactions to noise from normal aircraft operations. The address-based sampling method enabled a representative sample of 800 residents to be recruited from a simulated fly-over area. A graduated incentive structure kept respondents engaged, with higher incentives for higher survey completion levels and for each subsequent week of the test. Location data were also collected from respondents, because such data will be needed to estimate individual noise exposure from X-59. The survey methods test enabled a successful execution of the full survey process, with participation and response rates above expectations. Some additional lessons learned included the importance of automation in critical processes and the vulnerability of systems to network and server problems.

### sUAS Noise Community Responses

#### Responses in the United States

In a recent case, an Amazon drone pilot program for parcel delivery in College Station, Texas, has faced new scrutiny due to the complaints of local residents about the noise annoyance generated by the drones [206]. As a result, the second phase of this pilot program will not be pursued. In interviews with the neighbors of the area, some describe the drone noise as highly annoying and similar to a swarm of bees [207].

The Draft Programmatic Environmental Assessment (PEA) from the FAA for drone package delivery operations [274], while not a community noise survey, reports $L_{AE}$ values in its en route drone noise modeling without corresponding reporting of other noise metrics like peak sound levels. Community groups and consultants are converting $L_{AE}$ to other metrics, like peak sound levels, to interpret PEA modeling based on these other metrics [275]. The risk of incorrect conversion calculations by stakeholders may be avoided if these other metrics are reported in addition to $L_{AE}$.

#### Australian Study

Prior to and during commercial sUAS flight trial operations in Australia, communities were consulted to obtain feedback and provide a means to raise concerns [208]. Regarding noise, common issues highlighted included sound characteristics (in particular, ‘buzzing’ sounds) and quantities of overflights for residents situated in the vicinity of takeoff/landing zones. The feedback on sound quality prompted design development to reduce the effects of noise, while operational base siting and flightpaths were planned with the aim of managing overflight numbers. The trials highlighted that addressing community noise issues helped to secure further deployment permits.

#### European Union Studies

In the AMU-LED project, a social acceptance analysis was conducted on drones [209]. Questions regarding noise were addressed as part of a wider public acceptance survey conducted during demonstration trials in the cities of Amsterdam (The Netherlands), Cranfield (UK), and Santiago de Compostela (Spain). The questions asked were answered on a 3-point scale (“Yes,” “Not sure,” “No”), and the noise-related statements were:

- *“Drones are noisy”*
- *“Drones are quiet”*
- *“Drones are friendly for wildlife”*
- *“Drones are friendly for rural environments”*
- *“Drones are friendly for urban environments (people, buildings, etc.)”*
- *“Drones are environmentally friendly”*

In this study, only sUAS were involved and no noise measurements on the drone sounds were performed, so relations between noise exposure and annoyance could not be determined.

# Appendix E Regulation and Policy

## E.1 Environmental Review Framework (5.2.2.1)

Table 3: eVTOL-Relevant CATEX Provisions in FAA Order 1050.1G.

| CATEX Category | Criteria | Application to eVTOL | Notes/Conditions |
|---|---|---|---|
| Airport projects under $6 million | FAA projects with <$6 million in federal funding (established by FAA Reauthorization Act of 2024) | Vertiport at an existing federally obligated airport under this funding threshold can be processed as a CATEX | New in 1050.1G. Not automatic, FAA must still confirm no Extraordinary Circumstances (e.g., unusual public controversy, sensitive resources). |
| Flight procedures below 3,000 ft AGL | Changes at or below 3,000 ft AGL | Not specific to aircraft type. | Pre-existing CATEX provision from 1050.1F, FAA must still confirm no Extraordinary Circumstances |
| Flight procedures above 3,000 ft AGL | Changes above 3,000 ft AGL | Not specific to aircraft type. | New in 1050.1G. Previously an automatic CATEX. Now FAA must confirm no Extraordinary Circumstances before exclusion can be applied |
| Specific eVTOL/powered-lift procedure CATEX | Powered-lift (eVTOL) procedures regardless of altitude | Explicitly references eVTOL/powered-lift | New in 1050.1G. FAA must confirm no Extraordinary Circumstances |

## E.2 Vertiport Siting and Governance (5.2.2.2)

Table 4: Environmental review and approval pathways – federal and local decision authority.

| Site Type | Primary Jurisdiction | Environmental Review Lead | Key Authority and Implications |
|---|---|---|---|
| **FAA-Funded Airports**<br>(NPIAS or Other Federally Obligated Airports) | FAA (with Airport Sponsor) | Airport Sponsor prepares analysis. FAA is lead agency for NEPA review under Order 1050.1G | • **FAA determines level of review and issues final environmental finding (CATEX, FONSI, FONSI ROD, or ROD)**<br>• Subject to FAA policies and airport sponsor grant assurances and funding conditions<br>• FAA significance criteria apply if an EA or EIS is prepared and dictate how impacts are assessed<br>• ANCA restricts local operational limits without FAA approval |
| **Locally Funded Sites**<br>(Non-Federally Obligated, e.g., rooftop or local vertiports) | State and/or local authority | Local and/or state review, if required, under applicable land use and environmental laws | • **Local and/or state determine environmental review and approval, consistent with state law**<br>• Not subject to FAA NEPA review, including CATEXs unless a federal action is triggered<br>• Local discretion to define environmental impact criteria and community engagement processes, where permitted under state law<br>• At initial vertiport approval, local or proprietor authorities may establish facility operating conditions, including hours of operation, approved use cases, and phased or capped activity levels* |

* Facility operating conditions address land use and site operations, not aircraft operations or navigable airspace.

## E.3 Required or Optional Engagement (5.2.3.1)

Table 5: Environmental review levels and community engagement.

| Environmental Review Level | Public Notification Required | Community Engagement Required | Detailed Environmental Analysis | Examples |
|---|---|---|---|---|
| Categorical Exclusion (CATEX) | No | No | No | eVTOL procedures and vertiports at non-federally obligated sites less than $6M project; actions without Extraordinary Circumstances (e.g., unusual public controversy) determined by FAA |
| Environmental Assessment (EA) | Yes | Yes | Yes | Above $6M project at airport or eVTOL procedure if Extraordinary Circumstances (e.g., unusual public controversy) |
| Environmental Impact Statement (EIS) | Yes | Yes | Yes | Major new airport |

## E.4 Additional Existing Regulatory and Policy Documents Relevant to Vertiport Planning (5.3.2.1)

**Domestic Regulatory or Policy Guidance:**

- Airport Noise Compatibility Planning – 14 CFR Part 150 [193]
    - While this program is designed for conventional airports and the FAA NPR [199,265] specifically noted that Part 150 is focused on fixed-wing and rotorcraft operations, elements of this regulation, such as required noise modeling and noise evaluation standards, will likely be adapted and required of new AAM entrants.
    - Under 14 CFR Part 150, airports with a $L_{dn}$ 65 contour would fold UAM noise into the existing noise exposure map. Communities inside the contour could then receive mitigation through soundproofing or other airport-improvement program-funded projects. At FAA-funded, non-airport vertiport sites, however, no Part 150 process currently exists to establish a federally recognized contour for UAM noise, approve a mitigation program, or provide access to AIP funding for community sound insulation or other noise relief, although future policy changes could create such a pathway.
- FAA EB 105A [20]
    - This engineering brief provides interim guidance on initial design standards for the planning and construction of vertiports. The document focuses mainly on vertiport dimensions, design criteria, surface considerations, and obstacle-free areas. While this document does not provide noise limitations or mitigation policies, it does note the

importance of considering noise as part of the vertiport placement and overall design processes.

**International Regulatory or Policy Guidance:**

- EASA Prototype Technical Design Specifications for Vertiports [268]
    - This document includes environmental considerations and provides information regarding noise-sensitive approach and departure routes, flight profiles, and time of day operations.
    - Provides recommendations for noise modeling and encourages using community-based noise impact criteria.
- United Kingdom Civil Aviation Authority (CAA) – The Effects of Emerging Technology Aviation Noise [276] (annually updated)
    - An annual report from CAA tracking the ongoing developments of emerging aviation and its potential noise impacts.
    - Provides guidance to local authorities and developers on managing potential noise impacts on topics such as acceptability thresholds, site selection, and public engagement strategies.
- ICAO – Noise Abatement Operational Procedures [277]
    - The ICAO provides recommendations for noise abatement operational procedures across various documents. While these procedures were developed for traditional aviation, research can be considered for adapting best practices when planning vertiports.

**Non-Regulatory Guidance:**

- American Planning Association (APA) – Planning for Advanced Air Mobility [264]
    - Provides guidance on integrating AAM into comprehensive planning and zoning frameworks with an emphasis on noise mitigation strategies, community compatibility, and proper site planning.
- Los Angeles Department of Transportation – Urban Air Mobility – Policy Framework Considerations [278]
    - Provides vision of the roles and responsibilities of the city of Los Angeles that other cities may model when approaching emerging aviation technologies.
    - Provides land use policy considerations and permitting considerations for vertiport developers and operators.
    - The document emphasizes a community-focused, noise-centric approach to the vertiport planning process.
- ACRP Advanced Air Mobility and Community Outreach: A Primer for Successful Stakeholder Engagement [260]
    - Provides best practices and noise-specific considerations when conducting outreach related to vertiport operations.

# Appendix F Summary of Recommendations

The consolidated set of recommendations for each area of interest is provided below. This set includes those 2020 recommendations that have not been closed and the new 2025 recommendations. They are provided here in abridged form. The unabridged versions are provided in Sections 2.4, 3.4, 4.4, and 5.4.

## F.1 Tool Development and Experimental Validation (2.4)

Further development of validated noise prediction tools is required to support research and development of vehicles and their operations. It is recommended that:

SG1-2020-R1 System noise prediction tools be further developed for application to UAM vehicles and made available to the research and industrial communities.

SG1-2020-R2 Research be performed to develop conventions on how to handle control redundancies to obtain preferred low-noise trim conditions and to further develop the acoustic tools to handle aperiodic sources.

SG1-2020-R3 Prediction models for the highest amplitude noise sources be validated with experimental data for isolated and installed configurations, and that flight test data be acquired to better understand variations under realistic operating conditions, particularly unsteady conditions (e.g., maneuvers and transition).

SG1-2020-R5 A dedicated technology maturation effort be performed on the most promising noise mitigation technologies and that opportunities be sought to evaluate their efficacy in flight.

SG1-2020-R6 Surrogate or other reduced order model methods be developed so that designers can quickly determine the effects of design changes on noise early in the design process, and that sensitivities be fully implemented to enable optimization of low-noise vehicle designs and operations.

SG1-2020-R8 Manufacturers work with appropriate organizations to develop low-noise guidance for piloted operations and automated low-noise procedures for autonomous operations that are specific to their products.

SG1-2025-R1 A common research platform (i.e., vehicle configuration and/or canonical geometry) be established. From here, combined experimental and computational investigations can be conducted on the pertinent aeroacoustic phenomena.

SG1-2025-R2 In addition to measurements of radiated noise and integrated performance, experimental studies carefully characterize the unsteady aerodynamic interactions on (e.g., unsteady surface pressure) and around (e.g., inflow, wakes, etc.) rotors when possible.

## F.2 Ground and Flight Testing (3.4)

Several practices commonly used across the aeronautics industry should be strongly considered for near-term testing or future standardization. It is recommended that:

SG2-2020-R3 The "worst" case or the noisiest mode the vehicle will fly (under automatically controlled Variable Noise Reduction System provisions) be established. Additional work is recommended to define appropriate methods to evaluate acoustic dependence and variability with respect to the vehicle state.

SG2-2020-R4 A full assessment of anticipated UAM aircraft flight performance and operational environments be performed to support the development of any future certification procedures and/or standards.

Because UAM aircraft configurations and operations are far more diverse than those of conventional aircraft, innovative measurement methodologies are required to adequately capture the acoustic signature of these aircraft. It is recommended that:

SG2-2025-R1 Full-scale flight testing for a broad range of vehicle types be conducted to fully characterize landing and takeoff noise of UAM vehicles, as it is expected that this segment of flight will contribute to community noise.

SG2-2025-R2 Flight testing focused on assessing community noise impacts be conducted using both existing and innovative procedures.

SG2-2025-R3 Full-scale acoustic flight testing for UAM vehicles evolve to keep pace with evolving industry and regulatory needs.

SG2-2025-R4 As the efficacy of metrics and objective parameters relating UAM noise to human response become established, measurement techniques and best practices should be appropriately refined and disseminated throughout the wider community.

SG2-2025-R5 A standard exchange format be adopted for full-scale vehicle datasets to ease interoperation with agencies, companies and researchers.

## F.3 Human Response and Metrics (4.4)

Further development of metrics and validated predictive models of human response is needed to inform decision-making by UAM vehicle manufacturers and regulators. It is recommended that:

SG3-2020-R4 Validated models for audibility, noticeability, and annoyance to UAM aircraft noise be developed to assess their utility for assessing community noise impact.

SG3-2020-R5 The transmission of UAM vehicle noise through residential and commercial structures be quantified in order to evaluate the 20 dB loss assumed by current land use compatibility guidelines.

SG3-2020-R6 Measures of human response be developed and used as constraints in perception-influenced design. Ideally, such measures would be easily calculated and include sensitivities.

SG3-2020-R7 Comprehensive evaluation of metrics that supplement the day-night average sound level be performed for communicating community noise impact of UAM vehicle noise.

Efforts should continue, in the form of short-term and long-term noise testing, to improve understanding of UAM noise response and to provide data that establish long-term UAM noise exposure-response relationships. It is recommended that:

SG3-2025-R1 Community noise surveys should be conducted to support the development of long-term exposure-response relationships that can help inform policy. Evaluation of multiple metrics, in addition to those currently used, should be considered as part of that effort.

SG3-2025-R2 Assessments be made of the efficacy of objective parameters to describe the annoyance response to single-event UAM vehicle sounds. These objective parameters include, but are not limited to, conventional noise metrics, perception metrics, operational procedures, and persistent factors in communities that may affect noise perception.

SG3-2025-R3 Annoyance models be developed that can be applied to real-world conditions with complicated numbers and time structures of UAM vehicle flyover occurrences.

SG3-2025-R4 Continued development, updates, and validation of auralization tools be performed that account for source unsteadiness, transitional flight, prominent noise sources, and urban environment propagation.

SG3-2025-R5 Mechanisms be developed to provide guidance for consistent and scientifically valid methodologies for UAM vehicle noise community surveys, including a means of documenting lessons learned and guidance on reassessing results.

## F.4 Regulation and Policy (5.4)

It is recommended:

SG4-2020-R1 That at the national level, the FAA, in collaboration with other agencies and the industry, address certification, standards, and environmental reporting for UAM noise before these vehicles enter service.

SG4-2020-R2 That i) Industries be more proactive in approaching regulators to help them understand vehicle designs, noise characteristics, operating modes, etc., and to share relevant data, and ii) Regulators help the industry to understand the regulation process and policies, and identify specific data needs to bridge gaps in standards and procedures.

SG4-2020-R3 To collect more data in the field through R&D programs and to leverage data from manufacturers.

SG4-2020-R4 That regulators and policy makers work to clarify the boundaries of responsibilities in managing UAM noise, and support development of guidance for vertiport planning regarding both location identification and environmental assessment at the proposed locations.

SG4-2025-R1 To develop an Implementation Guide to support early and proactive community engagement by adding specificity to existing frameworks.

SG4-2025-R2 That AAM pilot studies be used as two-way learning platforms: collecting noise data and operational insights and then disseminating lessons broadly.

SG4-2025-R3 To establish a focused, multi-year expert task force and assign it to early implementations to ensure lessons learned are systematically captured and shared.