Emerging Technologies: The effects of eVTOL aircraft noise on humans

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Chapter 1
Introduction

1.1 The emergence of electric Vertical Take-Off and Landing (eVTOL) vehicles is a new area of aviation, and includes vehicles such as Unmanned Aviation Systems (UAS) which are also known as drones[1], and Urban Air Mobility (UAM) aircraft. This new technology has several potential uses, for example aerial mapping and photography, military surveillance, search and rescue, delivery, and air taxis amongst many others. This presents new challenges for noise legislation and understanding of how these types of noise sources may impact people on the ground. This report provides a concise overview of the current knowledge on the impacts of drone noise on humans over the past few years to the start of 2023. This is a relatively new research area, that has drawn significant attendance from researchers at the Internoise Congresses (2021 and 2022). There has also been a dedicated symposiun entitled Quiet Drones, held in Paris (2020 and 2022), that focused on the impacts of noise from drones. This CAP report highlights the main findings from these conferences, plus other relevant published research on the area to date.

[1] Although *UAS* is the regulatory term used by the CAA, there are various other terms in use within the sector for these types of aircraft. This is evident in the range of terminology used by the authors of the papers and studies which are summarised in this report.

Chapter 2

Internoise 2021

2.1 Internoise 2021 was held in Washington DC and this chapter describes some of the findings pertinent to drone noise impacts that were presented at this meeting.

2.2 **Nicholls** from the University of Salford presented findings from an investigation into the human response to Unmanned Aerial Vehicle (UAV) noise. The aim of the research was to aid in developing suitable psychoacoustic methodologies and metrics, specifically designed to quantify the community noise impact of these vehicles. The paper described a psychoacoustic experiment used to gather participant responses to UAV sound recordings, performing a variety of different operations at differing distances. It was found that loudness, sharpness, and fluctuation strength correlated strongly with perceived annoyance. The perceived annoyance, loudness and pitch all had a logarithmic correlation with UAV distance, suggesting that distance is a key factor that should be taken into consideration when assessing the impact of UAV noise on annoyance, not only due to acoustic characteristics, but the implications for non-acoustic characteristics as well. This could be investigated further using visual stimuli. Future extension to the research may include assessing the impact of introducing drone noise to a variety of soundscapes, evaluating the differences in psychoacoustic responses when introducing more accurate reproduction methods, such as virtual reality systems, and how these could be incorporated into a standardised human response measurement procedure.

2.3 **Bauer** et al presented work on Urban Air Mobility (UAM), which includes larger air-taxis, driven by multiple distributed propellers or fans, installed in a fixed configuration or as tilted wings/engines. The paper describes the ATEFA – Air Taxis: First Operational Noise Assessment project, which is a German nationally funded research project to examine the impacts on community noise from UAM. The main objectives of the study are:

- Describing noise sources for three selected generic (but realistic) air-taxi concepts.
- Establishing of generic traffic scenarios for realistic operational air-taxi use.
- Simulating single-event noise (with various noise metrics) and noise maps for all scenarios.
- Generating certification values according to ICAO Chapter 8 and 11 for concept assessment.

2.4 ATEFA will try to give first assumptions regarding metrics, being aware that annoyance will also depend on a larger number of non-acoustic factors, which may be influenced by the general question of acceptance towards this novel kind of air transportation. Due to the lack of available data, noise source modelling is inevitable for most of the project. Air-taxi operations will be simulated by generic traffic scenarios in a selected area of southern Germany, and community noise near verti-ports, but also “en-route” along the flight paths, will be computed. ATEFA will aim to show that the methodological approaches can provide sufficient accuracy for first assessment of air-taxi noise in the community of vertiports but also en-route. The validation of the methods will be achieved by comparison to a modern reference aircraft with known acoustic properties.

2.5 **Nixon and Dance** from London South Bank University described work on sound power levels emitted by commercial drones and the possible impact on rural areas. The aim of the project was to consider the sound characteristics emitted, specifically tonality and to determine the distance a drone could be heard from, with the different blade configurations, in a rural setting. By considering the different blade configurations within a rural setting, the role drones have within society is considered. Noise emission levels of the drone in flight were measured of no blades, quick release blades and carbon fibre blades,

2.6 The sound power level was determined per blade configuration. The quick-release blade types were found to have the highest values and the carbon fibre blades were found to be the quietest blade type. The drone in operation with no blades was significantly quieter especially in the mid-frequencies. The main difference in the blades is the material and weight. The type of drone used in this study (with the quick release blades) could be heard at a distance of 650m.

2.7 **Thalheimer** presented a paper on community acceptance of drones. This paper described some of the drones in use today, the major manufacturers and drone delivery services already well into development, and the current federal regulatory setting for community noise in the United States for various modes of transportation.

2.8 The paper concludes with a recommended new noise criteria approach (E-weighting), for FAA to consider adopting, that would account for the annoying “drone” of drones, could easily be measured in the field, and that would be compatible with existing community noise numeric limits. This newly proposed E-weighting method is an attempt to address the annoyance caused by the whine of small drone propellers. The advantages of the E-weighting method would include:

- The E-weighting filter shape could easily be programmed into a digital sound level meter for simplicity in performing drone sound level measurements in the field.

- There are a sufficient number of drone manufacturers from which to draw statistical averages for the eventual final shape of the E-weighting curve.
- Previously established and accepted community noise criteria numerical limits, expressed in A-weighted decibels, could still be evaluated for small drone noise using E-weighted decibels.

2.9 **Poling** (US) investigated community noise from a drone delivery distribution centre. This study evaluates potential drone delivery noise in the suburban community surrounding an existing retail distribution centre, assuming the facility were to be utilised as the hub of a future drone package delivery service. The predicted noise levels from the drone delivery service were compared to common community noise limits. This paper discussed several of the challenges that manufacturers and operators may face in getting their delivery hubs regulatorily permitted and options to reduce community noise from drones. Options to reduce community noise exposure by altering flight altitude and utilising different flight path routing strategies were also considered.

2.10 **Bauer**, from Munich Aeroacoustics presented work on community noise from urban air mobility (UAM) and its control by traffic management. In this paper, acoustically different air-taxi systems were used for air traffic noise simulations. The simulations start with baseline scenarios of equally represented taxi systems on fixed flight paths with several flight levels in a certain air-lane. The final fleets consisted of random air-taxi compositions with randomly populated flight paths. The results, based on common noise metrics and changes in the number of affected residents, could provide a first indication of how to reduce community noise by future UAM traffic management.

2.11 **Rochat** et al. authored a paper on the examination of spectral content, peak frequency relationships, and annoyance for unmanned aerial vehicle operations. The use of UAVs can expose communities to a type of noise not currently experienced, with current noise sources typically related to transportation operations (e.g,. aircraft, rail, road noise sources) and home activities (e.g., air conditioning units, lawnmowers). As such, it is important to understand the type of noise communities will experience with UAV operations. For this paper, a UAV flyover, hovers, landing, take-off, and manoeuvres were examined in terms of spectral content and the relationship of peak frequencies. In addition, the peak frequencies and relationships are discussed in terms of those typically associated with annoyance.

2.12 UAVs generate a variety of spectral content depending on model, operations, and the environment. Considering several perception-based parameters, UAV noise meets several criteria that lead to annoyance. UAV noise is new to communities, particularly for widespread use, and perception of such a noise source should be considered when evaluating impacts of UAV noise on communities.

2.13 **Zang** et al presented work on A Hybrid and Efficient Low-noise Assessment Platform for Urban aerial mobility (HELPU). This paper summarised the activities in the Aerodynamics and Acoustics & Noise Control Technology Centre (AANTC) in Hong Kong, towards reducing the environmental noise impact of UAM, including the understanding of the noise generation mechanisms, development of the prediction methods, estimation of the layout of UAM configuration impact and the assessment of long-distance sound propagation in a complex outdoor environment.

2.14 **Hui** et al from Auckland, New Zealand, authored a paper on the quantification of the psychoacoustic effect of noise from small unmanned aerial vehicles. The paper presented the results of a study evaluating the human perception of the noise produced by small quadcopter Unmanned Aerial Vehicles (UAVs). The responses of the participants are presented and compared with objective metrics of the sound measured during the noise event.

2.15 The results of the annoyance tests suggested that the effect of the flying conditions and altitudes affected how the participants perceive the UAV noise. It was found that UAVs were more annoying when being flown at low altitude compared with high altitude for a given UAV and flying condition. While annoyance was relatively strongly correlated with the A-weighted sound pressure level or other loudness-related metrics, such metrics did not fully explain how listeners rated the annoyance of UAV noise.

2.16 **Eißfeldt and End** from the DLR, Germany, authored a paper on sound, noise and annoyance, and information to strengthen the public acceptance of civil drones. The paper discussed results of a representative national study on the social acceptance of civil drones, taking a closer look at the effects of information about drones as a potential means to foster public acceptance. 832 participants answered telephone surveys during 2018. A set of 26 questions concerning various aspects of public acceptance were asked, including associations with the term drone, personal experiences, individual support of potential uses, personal concerns, and thoughts about general regulation. There was a split in responses between those in favour of drones versus those who were against the use of them. Male respondents had a more positive attitude toward civil drones than female respondents, and younger study participants showed higher acceptance rates than older ones. Knowledge about drones and their uses can play an important supporting role in broadening social acceptance. The findings highlighted the role of well-planned information campaigns as well as community engagement in managing the contribution of drones in future urban soundscapes.

2.17 **Hellweg and Fleming** presented summaries of the 2018 and 2020 Technology of Quieter America workshops with respect to unmanned air systems (UAS/UAV) (drone) and aerial mobility. The 2018 UAS/UAV and 2020 Aerial mobility workshop reports provide information on the many new applications for UAS/UAVs and aerial mobility vehicles that are available and expected to be implemented over the next few decades. The authors concluded that: “a common theme at both workshops was the need for further research related to aerial mobility noise, including but not limited to noise reduction methods, data acquisition, annoyance, standardisation of metrics, modelling, testing and certification”.

2.18 The 2018 workshop focused on noise emissions of UAS/UAVs in sizes up to and including those capable of carrying packages. Pilot programmes for fast delivery of medical supplies already exist and delivery of consumer products is on the horizon. Less emphasis was placed on larger devices proposed, for example, for urban air mobility (UAM), whose implementation is expected further in the future.

2.19 The 2020 e-workshop focused more on larger aerial mobility vehicles; however, presentations were on vehicles that ranged from small drones to aerial taxis. The authors stated that attendees at both workshops expressed a common commitment to partnering with others in government, industry, and the public toward integrating drones into the national airspace.

2.20 **Aalmoes and Sieben** from the Netherlands presented findings from a visual and audio perception study that examined both audio only and audio-visual stimuli of hovering and fly-over events in a virtual reality setting. In addition to the drone sounds, more familiar sounds are also evaluated, namely a helicopter and a lawn mower sound, with and without a visualisation. Drones were found to be more annoying than helicopters, but less than lawn mower sounds. Visual perception and urban background sound levels seem to have a smaller influence when evaluating drone annoyance than previously expected compared to quieter background noise levels. Main factors that have an influence are the characteristic sound of the drone and the attitude towards drones.

2.21 **End** et al discussed a study examining gender differences in noise concerns about civil drones. This paper was presented at the ICBEN Congress, 2021. The German study was a telephone survey of over 800 participants in 2018, on behalf of the DLR. There was a significant difference found when asking the participants whether their general attitude towards civil drones was rather positive or rather negative, with females expressing more negative views than males. The following seven areas of concern about civil drones in explaining female and male respondents’ general attitudes were assessed: concerns about noise, concerns about damages and injuries, concerns about liability and insurance, concerns about the violation of privacy, concerns about crime and misuse, concerns about animal welfare, and concerns about traffic safety.

2.22 The findings indicated that concerns about noise constituted the only area of concern which significantly contributed to the explanation of female respondents’ attitudes. Concerns about damages and injuries explained male participants' attitudes best.

2.23 Apart from noise concerns, significant gender differences were found regarding five out of the six other areas of concern. Female respondents more frequently reported to be concerned about damages and injuries, violation of privacy, crime and misuse, animal welfare and traffic safety. Only with respect to concerns about liability and insurance was there found to be no significant gender difference. The authors suggested that future research should further examine whether gender differences in drone acceptance could in part be driven by certain types of confounders which might frequently occur between females and males. For example, the estimated number of hours of prior experience with these types of vehicles could be assessed. They conclude that a lower prevalence of a positive general attitude towards civil drones and a higher prevalence of (noise) concerns about these vehicles among females might indicate a higher risk of being annoyed by drones. If annoyance by civil drones was more widespread among females, this group would perhaps also be at higher risk of health impairments from drone traffic.

Chapter 3

Quiet Drones 2020

3.1 The Quiet Drones Symposium was held as a virtual conference in Paris, 2020. The description of the meeting stated:

3.2 “Enormous progress has been made on drone technologies in the last decade and the number of professional drones is increasing dramatically and is now much higher than the number of conventional aircraft.

3.3 Safety, security, and privacy have controlled the development of drones up to now, but noise has become an issue in residential areas and environmentally sensitive areas such as National Parks. On the other hand, ultra-silent machines represent a problem for privacy and security.

3.4 The Symposium provided a venue for researchers on drone noise to meet with manufacturers, users and those engaged in designing innovative applications for this new technology.”

3.5 **Torija Martinez** from the University of Salford presented a paper on Drone Noise, A New Public Health Challenge? This paper introduces and discusses the main challenges and research gaps on noise effects of drones. It is explained that drone noise is highly tonal and has irritating frequency and amplitude modulations due to the varying rotational speeds of the rotors. It is anticipated that they will fly closer to people than currently experienced with other aircraft, and in larger numbers. Communities not currently affected by aircraft noise will probably be impacted by the introduction of UAM vehicles. Some challenges and research gaps include:

- It is uncertain whether the current evidence of health effects of aircraft noise will be of application. If not, new evidence will need to be gathered as to health effects of drone noise.
- There are neither metrics able to account for the characteristics of drone noise nor information about acceptable levels.
- There is no understanding on how the deployment of drones will affect the perception of current urban and rural soundscapes.
- Community annoyance will be different depending on context, e.g., drones delivering medicines to remote areas versus drones delivering parcels to neighbours.

- For planning purposes, exposure-response functions for drone noise will need to be derived. This introduces the challenge of how to predict long-term effects.

3.6 The paper outlines the main noise characteristics of drones, and states the need for further research to:

- understand the effects of drone noise on public health and wellbeing,
- develop metrics to assess community noise impact of drones,
- define acceptable levels for drone noise,
- inform best operational practices for drones regarding noise profiles, and
- innovate in the approaches to predict long-term noise effects when drones operate at scale.

3.7 **Burgess** presented a paper on drone delivery and noise regulation in Australia. This study involved using two suburban areas around Canberra and Brisbane in a trial looking at delivery drone noise and annoyance. The payload of up to 1.5 kg is delivered by a drone designed to keep the package steady and level to avoid spill for products like brewed coffee. After approving the trial and acknowledging that the current noise regulations do not adequately address noise from drones, in 2019, the Federal Department initiated a review.

3.8 The main concerns from the participants in the trial were the buzzing noise from the drones, the high number of overflights that the people who live close to the base of the operations are exposed to, and the annoyance of neighbours to those people who have frequent drone deliveries. The drone company, Wing Aviation have used the responses from the trial, which has led to changes in operation with the use of a drone that has lower noise levels and a less annoying noise signature plus additional attention to flight paths.

3.9 **Clark and Biziorek** authored a paper on a whole-systems approach to building knowledge about human reaction to UAV/UAS. This paper describes lessons that can be learnt from general and commercial aviation for the UAV/UAS industry. A methodological framework is proposed for building knowledge to inform systems and operations development within the short-time frame sought by this emerging market. The authors also report on planned research studies in Arup's immersive aural and visual simulation facilities – SoundLab and iLab – to build knowledge about human responses to this mode of transport.

3.10 The paper explains the differences between the types of aircraft under consideration, namely:

- **UAM** (Urban Air Mobility) which are manned vehicles designed to transport people within cities, usually using eVTOL (electric Vertical Take Off & Landing).
- **Drones** which are unmanned aerial vehicles (**UAV**) that can be small or large and used for pleasure, surveys, emergencies, or deliveries. In relation to drones, the term **UAS** (Unmanned Aerial System) can also be used, to describe a UAV plus all the elements to control it (e.g., remote control, communication system etc).
- **Longer-range electric/hybrid aircraft** for use on regional/short-haul aircraft routes can also be considered as part of the future of aviation.

3.11 It is explained that the challenges presented in the introduction of UAV/UAS involves building knowledge and overcoming a number of key challenges related to factors such as:

- Regulation.
- Vehicle testing and certification.
- Operational Safety.
- Vehicle-to-vehicle communication.
- Cybersecurity.
- Energy sources.
- Airspace management.
- New infrastructure.
- Developing new business markets.
- Standardisation of noise assessment.
- Human response to noise and visual pollution; and
- Public readiness.

3.12 This paper describes two specific challenges: human response to noise pollution and public acceptance, highlighting the need to engage with social scientists to build knowledge. The authors conclude that an approach to building knowledge will need to be large-scale, ambitious and embrace different research methodologies. There is an urgent need to build knowledge to maintain proposed implementation and ultimate acceptance.

3.13 There is already funding support available in some countries (e.g., Future Flight Initiative in the UK; the Advanced Air Mobility National Campaign in the United States) for research in this field, but there will need to be multiple initiatives and collaborations for knowledge to be built to inform the ongoing, rapid development of UAV/UAS technologies.

3.14 **Cléro** et al presented the French MOSQUITO Project – a fast estimation approach for urban acoustic environments. This study aims to perform a first evaluation of the necessary requirements to ensure compliancy with a high-density population environment and public acceptance of drones. This paper primarily focussed on the acoustic element of drone noise; however, some aspects of human impacts are discussed. The authors explain that the drone aircraft itself presents a noise signature that is uncommon to classic urban soundscapes. Its spectral content is very different from already present noise sources and its occurrence is VTOL specific (time varying, over a certain duration, low flights, hovering etc.). In addition, other factors such as the surprise of a noise source coming from the sky, the fear of a drone falling, or the fear of surveillance are worthy of further investigation.

3.15 **Duncan** et al used community noise mapping to study how to reduce noise impacts of drones by optimising flight routes to both increase sound masking and reduce population exposure to noise. The study explores a methodology using sound propagation modelling of drones coupled with existing community noise maps and background sound level data to assess various flight route options and flyover and hover levels in the context of a residential neighbourhood.

3.16 Four different routes were examined, with the finding that routing over undeveloped land results in the lowest noise exposure to the study population, but routes over higher populated areas following roadways may result in lower impacts due to masking by traffic noise. The noise benefits of randomising routes are also discussed, particularly for the population near the drone depot.

3.17 **Eißfeldt** presented a paper entitled “Acceptance of drone delivery is limited (not only) by noise concerns”. This was the same study described earlier that found gender differences in attitudes towards drones, though the results were expanded to include medical use, which revealed approval rates in the total sample much better then, with 3 out of 4 approving this usage, but furthermore, in this case women demonstrate even slightly higher approval of drone delivery than men. The NIMBY (not in my back yard) effect is discussed in relation to drones, which is the imbalance between a generally supportive attitude towards a new, often technological development and the lack of acceptance of change in one’s direct environment connected with it. Even among those who support drone usage and would consider using drone delivery themselves, the motivation to accept drones as part of their personal environment is limited.

3.18 The results of this study revealed that the critical attitude toward drone delivery in general is based on concerns about transport safety, noise, and animal welfare. This echoed findings by Dannenberg (2020) who found that when attitudes towards delivery drones were studied in German towns, noise was confirmed as a disadvantage of drone delivery by two-thirds of the respondents. Other negative responses that were observed included 'job-loss effects' (68%), 'stress due to drones flying around' (67%) and 'visual clutter' (57%). On the positive side, 'environmental friendliness' (79%) and 'reliability of service' (73%) were the top-rated benefits anticipated for drone delivery.

3.19 Hellweg and Herreman reported on ANSI/ASA standards activity on the measurement of UAS noise. The American Standards Committee S12 on Noise is developing an American National Standard for the measurement of sound power levels from small (under 55 pounds, i.e. 24.95 kg) unmanned aerial systems (UAS) in an anechoic chamber[2]. A working group of around 30 members have the goal of developing a small UAS sound power level measurement standard that is:

- repeatable and independent of the environment, i.e., temperature, wind, background sounds, precipitation, etc.
- a uniform test procedure following specified operating conditions.
- a method that provides users with data that can be used to predict ground sound pressure levels at specified locations in many different environmental and geographical conditions.

3.20 When approved, the ANSI/ASA standard will provide small UAS sound power levels that can be used for:

- product-to-product comparisons,
- determining effects of noise control methods on specific models,
- purchase specifications,
- determining community sound pressure levels using advanced software programs or directivity information (which can be determined during the sound power level measurements in an anechoic chamber).

3.21 **Torija and Clark** published a paper in the International Journal of Environmental Research and Public Health entitled: 'A Psychoacoustic Approach to Building Knowledge about Human Response to Noise of Unmanned Aerial Vehicles'. This paper describes the main acoustic and operational characteristics of UAVs, as an unconventional noise source compared to conventional civil aircraft. Gaps in the literature and the regulations on the noise metrics and acceptable noise levels are identified and discussed. The paper contains a description of the health effects linked to civil aviation and how they may be used as a basis to assess the human impacts of drone noise. Alongside annoyance responses,

[2] An anechoic chamber in this context is a room designed to completely absorb reflections of sound waves. They are also often isolated from sound waves entering from their surroundings.

depending upon the operating restrictions, effects on sleep and children's learning should be relevant and immediate considerations in communities exposed to UAV noise. Effects on cardiovascular and metabolic ill-health, if present, would take several years to manifest; so, it may be more challenging to study in the initial stages of developing UAV operations and systems. The authors stress that this is not to suggest that planning for UAVs should ignore cardiovascular and metabolic health; however, it may be necessary to take a precautionary approach and to rely on the exposure-response functions of the aircraft noise effects on these outcomes to estimate the effect of UAVs on public health in the short term.

3.22 In terms of recommendations for research needs, the authors stress the need for urgency. NASA's white paper has summarised the research gaps and discussed recommendations to address the barriers associated with Urban Air Mobility noise. This white paper suggests the following areas of interest:

1. prediction tools and technologies for noise reduction.
2. ground and flight noise testing.
3. human response and metrics; and
4. regulation and policy.

3.23 It is explained that simulated auralisations (immersive sound recordings) and visualisations of UAVs presented in laboratory settings offer a well-controlled, fully calibrated immersive listening environment for laboratory studies and could be used to address the following challenges in relation to human response and public readiness:

- Develop knowledge about human responses to the sound produced by these new aerial vehicles and understand public acceptance.
- To evaluate the sound emissions of vehicles to identify the appropriate metrics to describe the exposure. This information could also inform certification standards, assessment methods and policy. The development of metrics will need to be informed by human response to noise, as well as the ability of individuals to understand what the metric represents for communicating environmental impacts with communities.
- To create virtual reality sound demonstrations to demonstrate the new technologies in their context to communities.

3.24 The authors present a range of metrics that may be explored in such studies (Table 1).

Sound Quality Metrics	Human Response Outcomes [1]	Psychoacoustic Factors	Other Factors
Loudness	Annoyance [2]	Pleasantness/Eventfulness	Visual impact
Sharpness	Audibility	Calmness/Vibrancy	Ambient noise
Tonality	Physiological responses		Community soundscape
Roughness	Sleep disturbance		Indoor versus outdoor perception
Fluctuation strength	Cognitive effects		Contextual/cultural/population variation
Impulsiveness	Perceived stress		Vehicle type variability
Sound Exposure Level (L_{AE})			Number of events
L_{Aeq}, T			Time of day
$L_{A,max}$			Altitude
			Attitudes to source/operators
			Perceptions of safety/trust

[1] Plus additional factors identified through qualitative research. [2] ISO/TS 15666 methodology [42].

Table 1: Variables to be explored to build knowledge of the human responses to UAVs

Chapter 4
Internoise 2022

4.1 **Schlittenlacher and Wales** presented findings from a study on helicopter-like sounds in urban background noise. The background to this study is that eVTOLs rely on rotors or similar propulsion for the desired vertical take-off in urban air mobility, and in contrast to a helicopter with a single main rotor, eVTOLs allow for more sound design opportunities using a combination of several rotors.

4.2 The authors explain that most aircraft noise metrics are based on the equivalent A-weighted sound pressure level (L_{Aeq}). They explain why such metrics are problematic for rotorcraft and urban air mobility and incomplete for several reasons:

- These metrics do not consider that the sounds occur within background noise. Therefore, they cannot reward a clever sound design that “hides” the vehicle sound within the urban background noise.
- They do not consider the temporal shape of a sound. This is important for eVTOLs because a more continuous and less impulsive sound is quieter at the same L_{Aeq} (Schlittenlacher and Moore, 2021).
- The metrics ignore further aspects of perception e.g., spectral loudness summation.

4.3 The time-varying partial loudness model by Glasberg and Moore is suggested to overcome such limitations.

4.4 The aim of this study was to examine to what extent additional metrics like sharpness, roughness, tonality, or impulsiveness improve annoyance predictions, and to what extent the consideration of additional metrics leads to improvements in annoyance due to correcting for the limitations of linear correlation models or minor discrepancies between calculated and subjectively evaluated loudness.

4.5 The experiment was conducted online in the participants’ homes. They were asked to evaluate the annoyance of burst sequences in background noise with burst durations of 1, 5 and 20 ms. The authors compared these responses to those from a previous study and could then assess whether impulsiveness adds to annoyance or is already captured by loudness ratings. Using two different background sounds at different levels also allowed for measurement of its impact on psychoacoustic annoyance.

4.6 All stimuli consisted of a background noise and a helicopter-like sound, which was a sequence of noise bursts. One of the two background sounds was recorded at a busy street ("loud background") and the other in a suburban area ("soft background"). The loud background was always presented at the same sound pressure level as the reference sound that participants were asked to rate for natural loudness prior to the study starting (60-65 dB), the soft background level was 10 dB lower. Both background sounds had a duration of 2 seconds. The sequences with burst durations of 1 and 5 ms (target sounds) were each compared in annoyance to a sequence with burst duration of 20 ms (reference sound).

4.7 The results suggested that sequences with shorter bursts were perceived as more annoying than those with longer bursts. A sequence with 1 ms bursts needed to be 6 to 8 dB L_{Aeq} lower to be equally annoying as a sequence with 20 ms bursts. The authors state that this difference is ignored by metrics that are based on equivalent sound pressure. The effect of the level of the background noise amounted to about 1.5 dB in the comparison of level differences for equal annoyance (LDEA) for the difference of 10 dB in background noise level. They conclude by stating the role of impulsiveness in annoyance from rotorcraft noise seems to be already captured by its effect on loudness.

4.8 **Aalmoes** et al presented a discussion on the challenges of public acceptability of drone noise. The paper discusses the importance of non-acoustic factors and subjective measures such as demographic, perception and emotional factors such as attitudes towards drones and air taxis.

4.9 The authors propose that there are several processes that may assist in gaining public acceptance of UAM. Understanding public concern, informing communities on the need and benefits of operations, and educating about expected annoyance, preferably with participation opportunities in the decision process, helps to gain trust and can shape public's attitude towards drones. These are discussed in more detail.

- Understanding public concern: the findings from the ANIMA (Aviation Noise Impact Management through novel Approaches) project are valid for UAMs in terms of engagement with communities, and annoyance. The International Civil Aviation Organisation (ICAO) Balanced Approach, where reduction at the source, land use planning, noise abatement procedures, and operating restrictions are used in noise management for airports, may also be translated for UAM noise management.
- Dealing with change: For example, local shifts in noise exposure. Such shifts mean a different group of people is exposed to noise, which can lead to more complaints as they are not accustomed to these levels of noise. New, or more, noise for affected populations can generate proportionally higher numbers of complaints than expected.

- Other personal and social factors: Noise sensitivity should be considered in drone noise research, as well as attitude outcomes such as trust in authorities, history of noise exposure and expectations of residents. Any relationship between annoyance and age should also be explored.

4.10 The opportunities for improving public acceptance are discussed. For example, benefits of the application can help reduce or downplay the perceived (negative) impact of drone noise. Informing and educating noise-affected communities are essential when introducing drone services. The paper outlines some of the activities occurring to examine public acceptability of UAM.

- Useful applications: Explaining that focussing on positive uses and outcomes for the community may override the negative associations with the noise source.
- Information and education: The importance of informing and educating communities is stressed. Although there is some evidence that being able to see drones may lessen the annoyance effect, there is also an argument that this may provoke a stronger annoyance response in other people. The authors cite work by Asensio (2007), which describes four participation techniques for an increased level of community engagement and relations with the operators, allowing for increased levels of acceptance: information, consultation, participation, and empowerment.

4.11 The authors describe some existing work that is currently underway to deal with public acceptance of UAM. Firstly, drone perception studies are important to obtain data on the annoyance response to drone noise. Findings have suggested that drone noise tends to be more annoying than aircraft or road traffic noise. Gwak et al found “a significantly higher level of annoyance towards medium and large drones when compared to aircraft, but smaller drones showed an actual decrease in annoyance compared to aircraft at the same level of loudness”.

4.12 A previous study by Aalmoes has found drones to be more annoying than helicopters, which it is suggested, may be due to the perceived usefulness of helicopters compared to drones at this stage. Further research is underway to explore the association with perceived usefulness and annoyance due to drone noise.

4.13 This study also investigated the non-acoustic factors in drone annoyance. The results indicated that a drone is seen as more annoying when it hovers compared to when it flies by. It is explained that this may be an issue for the implementation process, mainly at a busier central point where drones fly to and from. This study showed no significant difference in annoyance response between a drone that visibly flew over or was only audible.

4.14 The Dutch Drone Delta (DDD) is described in the paper. The DDD is an interest group that consists of future stakeholders of the Dutch UAM network. The DDD aims to accelerate the safe and effective deployment of UAM in the Netherlands with studies, questionnaires, and pilots. It consists of five areas: addressing social acceptance, long distance operations of drones, integration of unmanned systems with manned aviation, drone delivery, and finally UAM.

4.15 The EU-funded Air Mobility Urban-Large Experimental Demonstrations (AMU-LED) project's aims were to design and deliver a comprehensive concept of operations and definition of urban air missions, and to verify and validate this concept through simulations and a real-flight demonstration campaign. The project will allow UAM stakeholders to determine several use cases applicable to logistics and urban transport of passengers and to design or integrate a UAM environment, test airborne platforms, and assess security, sustainability, and societal impact.

4.16 The real-life flight demonstrations are taking place in various European countries, including the UK, over a two-year period from 2022. During the two-year project period, a hundred flying hours will be logged above urban environments.

4.17 The aim is that these demonstrations allow the project to get real data on the level of acceptability of UAM. Three focus groups have been set up in each of the participating countries to analyse their level of acceptability on different aspects of UAM. The focus groups are composed of 20 people from different backgrounds and age groups, who will be asked to respond to the same survey in two phases: a first phase, without seeing the drones flying in real life, and a second, after seeing them fly. The idea behind the two-phase interview is to prove how perception (and acceptability) changes once the public can understand fully what drone flights entail. With the results of the surveys, recommendations will be made to the authorities on how to introduce UAM in cities in an acceptable way to the public.

Chapter 5
Quiet Drones 2022

5.1 The second Quiet Drones Symposium was held in 2022 and covered a range of topics relating to all types of eVTOL aircraft.

5.2 **Becker** presented findings from a German Environment Agency study, that explored whether it was possible to apply German aircraft noise assessment methods, or the ISO standard 9613-2 to calculate noise levels emitted from drone usage. Due to both methods having drawbacks for drone noise calculation, the German Standard organisation (DIN) is developing a new standard which will be more suitable for drone noise.

5.3 This study looked at three flight scenarios and sound calculations were performed for:

A. Delivery of goods to the front door

B. Geo-exploration of an area by slowly flying over it

C. Light show with several hundred drones

5.4 Scenarios A and B were modelled over the city of Berlin, and scenario C was assumed to be over a flat area. It is explained that in Germany industrial noise is not permitted to exceed 55 dB L_{Aeq} during the daytime (06:00 to 22:00) in residential areas. Due to the tonality of drone noise increasing annoyance, the authors propose that an addition 6 dB would need to be added to the levels in the existing guidelines for industrial noise limits to compensate. It is concluded that if the noise from drones were to be assessed based on a rating level of 55 dBA, even one minute of operation per day in the vicinity of residential houses would exceed the limit. The authors suggest that in order to let drones operate in the vicinity of residential areas, a significant noise reduction is needed. However, if drones are flying above residential houses at a minimum distance of 100 m, noise limits are not thought to be exceeded, even if 100 drones per day were passing by. The results indicate that there appears to be a critical minimum distance between drone flight and residential properties in order for noise limits not to be breached.

5.5 **Jackman** presented a paper on the social and political implications of increased drone noise in the UK. The paper highlights the relatively new research area of impacts of drone noise and discusses the variables involved, such as human and nonhuman factors, spaces (urban and rural), and understandings (commercial, regulatory, public) of the issue and impacts of drone noise. The issues surrounding regulation of drone activity are described, including the challenges associated with varying vehicle sizes, individual characteristics, and the different environments in which they operate.

5.6 The paper discusses some of the research findings on annoyance responses to drone noise, and how contextual factors may be of importance, such as the level of background traffic noise (i.e., road, rail and non-drone aircraft noise). Settings with a lower level of traffic noise resulted in a higher perceived level of drone noise. Perceptions of usage are also highlighted, such as the trend for greater acceptance of operations providing a service such as search and rescue, as opposed to private delivery flights.

5.7 Attention is drawn to the potential impacts of drone flight on non-humans, and impacts on wildlife remains an understudied area of research given the possible stressor effect of drone operations on animals. Jackman cites Mulero-Pázmány et al. (2017) who classified the ‘reaction caused’ by drones into several categories: ‘none’, ‘alert reaction’ (i.e., showing ‘increased attention or alert’ towards the drone), and ‘active reaction’ (i.e., ‘responding actively’ towards drone by ‘fleeing or attacking’). It is thought that birds in large groups are the most affected by drone noise and are the most sensitive. The paper describes studies investigating drone noise on birds and their subsequent behavioural and physiological responses. Impacts of drone flight noise on mammals such as black bears are also discussed, as is the importance of considering how the introduction of drones may affect all types of wildlife, particularly the understanding of visual and auditory stimuli.

Chapter 6

EASA Report

6.1 One of the main gaps in eVTOL emerging technologies such as UAS and UAM, and their noise impacts on humans is the exposure-response curves seen in aircraft noise research, and the subsequent development of threshold limits and guidelines for noise exposure. In 2021 the European Union Aviation Safety Agency (EASA) published a report that attempted to address this and develop a human exposure-response relationship with respect to single flyover events of UAM vehicles.

6.2 The study was conducted on 40 participants and was based in Amsterdam, with a laboratory design, and examined the annoyance response to helicopter and rotor-based drone vehicles. In this study both (unmanned) drone vehicles and VTOL vehicles that can be used to move people around, also known as air taxis, were considered. Usually exposure-response studies are conducted in the field, but due to the new and experimental nature of current drone operations, this is not yet possible. Instead, laboratory-designed studies allow for measurement of short-term responses to noise, which may help predict what the long-term responses may show. Only recordings of flyovers were played in this study, no hovering or take-off or landing noise was played.

6.3 The participants were played the sound events through headphones and were asked to report their annoyance on a scale by moving an indicator on a slider between a value representing ‘not annoyed at all’ and ‘extremely annoyed’. Each event was a pre-determined sound sample from a UAM-vehicle or a helicopter and was played at different sound levels. The noise sources included two helicopters, four multicopter drones, one air taxi and one fixed wing aircraft model. The pre-determined sound levels were spaced in 10 dB(A) SEL steps, and only the sound level that the participants were subjected to was adjusted. For each of the vehicles that were presented, the total number of highly annoyed scores was counted for each sound exposure level. This led to an annoyance curve for the percentage of events that cause the respondents to be highly annoyed against sound exposure level (dB(A) SEL).

6.4 Logistic regression was applied to the data, and the resulting exposure-response relationship for annoyance responses to drone noise is shown in Figure 1.

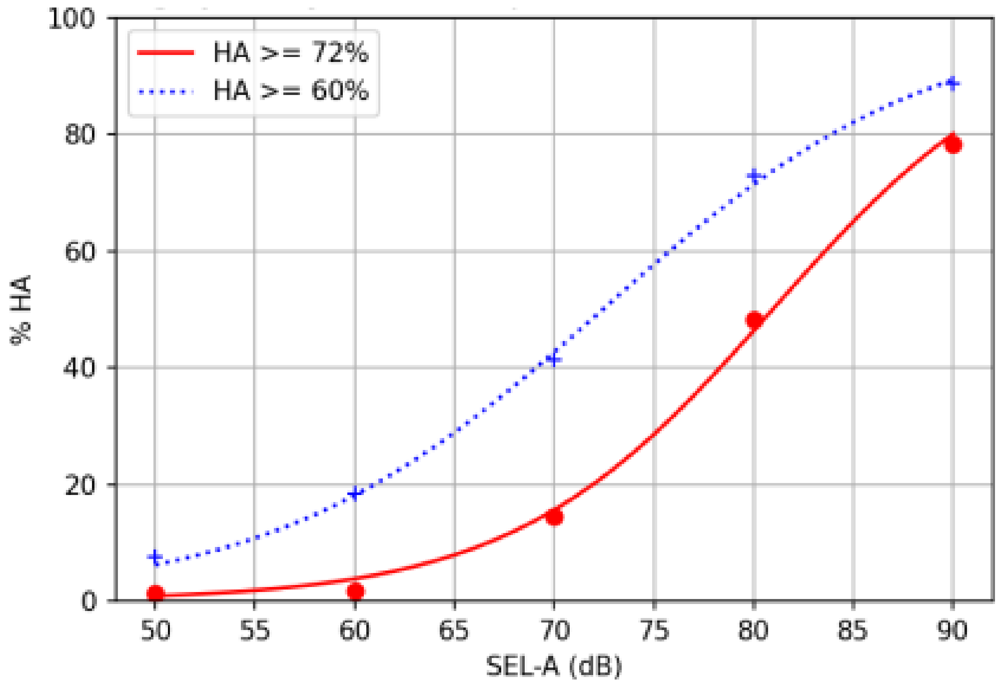

Figure 1: Combined dose-response for eVTOL vehicles (four different multicopter drones, one fixed-wing drone, and one air taxi)

6.5 The criterion chosen for "highly annoyed" was a score over 72% of the presented annoyance-scale, in accordance with that used for aircraft noise studies. The 60% annoyance threshold was also examined, which is comparable to the 5-point annoyance scale. Participants also completed a post-test questionnaire related to whether they recognised the sounds, their noise sensitivity, and their attitudes towards drones.

6.6 Noise sensitivity of the participants was measured using a six-point scale (Weinstein Noise Sensitivity Scale); noise sensitivity was not found to be associated with being highly annoyed from drone noise. 22 of the 40 participants recognised the noise being played as being from drones, therefore analysis of how recognition could affect attitudes towards drones and annoyance could not be undertaken due to the small sample size.

6.7 The results of the study indicated that annoyance was higher for drone noise compared to helicopter noise, particularly above 70 dB(A) SEL. The response to the fixed-wing vehicle was similarly rated to that from the drones, and the authors explain that this may be because they had similar electric engines, which exhibit similar noise characteristics. The air taxi annoyance rates were similar to those from the drone noise and was rated as more annoying than helicopters at the higher SEL values. It is stressed that only one air taxi was included in this study, and the importance of investigating different models and their effect on annoyance is highlighted.

Chapter 7

Other research findings

7.1 **Ramos-Romero** et al published a paper discussing the requirements for drone operations to minimise the noise impact on communities and which presents a modelling framework for setting recommendations for drone noise.

7.2 The aim of this research was to inform drone stakeholders of the specific requirements of drone flight in terms of distances from residential properties, based on noise metrics specified as guidelines for acoustic targets in the receiving environment, such as the WHO Guidelines. The authors explain that drone noise is typically different to aircraft noise in terms of tonality and high-frequency broadband noise, therefore current noise metrics used to evaluate aircraft noise are not suitable for use with drones. However, until enough robust evidence on the human response to drone noise exposure is gathered, it is explained that existing aircraft noise metrics and recommended targets could be used to inform regulation of operational drone procedures. The paper produces plots of the distance between the drone and the building façade against indoor maximum noise level assuming an open window, and compares the speed of flyover, and different models of drone, one of which is shown in Figure 2.

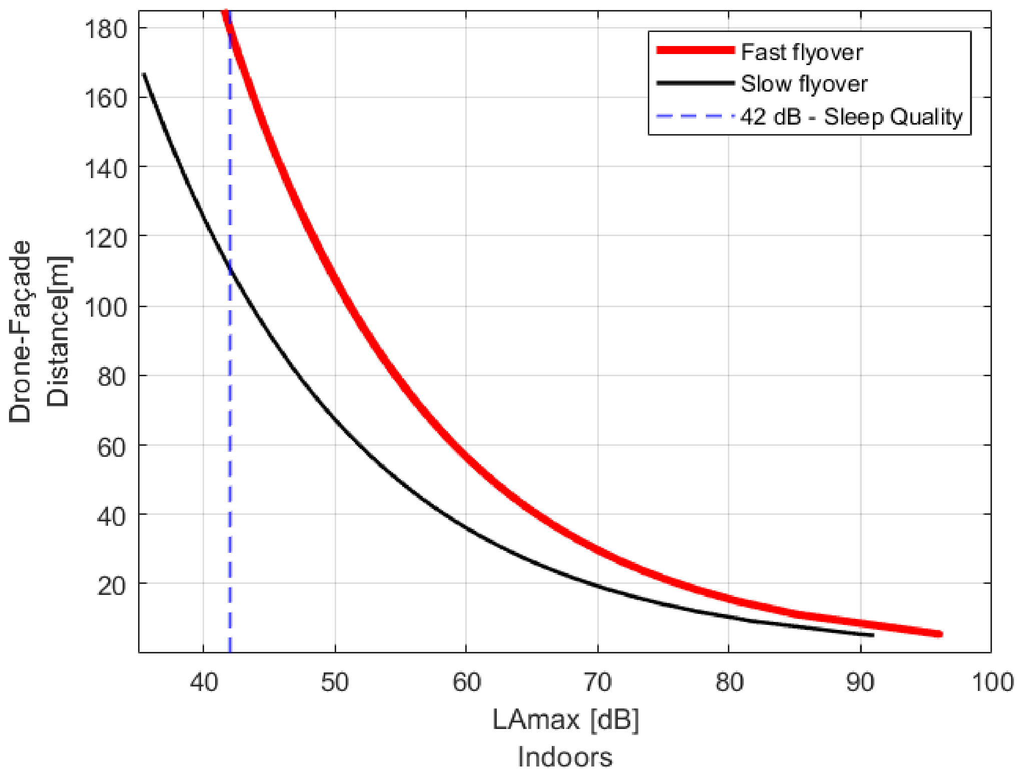

Figure 2: Drone/façade distance based on the $L_{Amax,\ indoors}$ for drone GD28X at fast and slow flyover operation near a façade with a conventional window open area 0.05m.

7.3 Figure 2 shows the blue dotted line at 42 dB $L_{Amax,\ indoors}$ which represents the WHO guidelines threshold of 42 dB $L_{Amax,\ inside}$ for "Waking up at night and/or too early in the morning". For a given drone (GD28X) operating near a window with an open area of 0.05 m^2, the drone-façade distance to meet WHO recommendations for sleep quality "waking up in the night and/or too early in the morning" ranges between 111 m (slow flyover) and 179m (fast flyover). A similar plot is presented for drones with smaller dimensions, lighter total take-off weight, and fewer rotors that could operate closer to the community than drones with larger proportions and more rotors, to comply with the acoustic target indoors. The authors conclude that this modelling framework can be used to define operational restrictions (e.g., in the form of minimum drone-façade distances) to meet recommended noise targets and avoid significant noise impacts on communities inside dwellings.

7.4 **Schäffer** et al published a systematic review on drone noise characteristics and noise effects on humans in 2021. The review describes the process of reviewing the available literature, the current state of knowledge at the time, and the gaps remaining in the knowledge to date. The first section of the review looked at drone noise emission characteristics and suggested that the source strength primarily depends on the drone model and payload, as well as on the operating state or the flight manoeuvre.

7.5 The findings of the effects of drone noise on humans revealed that, although based on the limited data available at the time of the study, the available research findings consistently suggested that drone noise was more annoying than road or aircraft noise, due to the tonal characteristics and the presence of high-frequency broadband noise. The authors explain that various non-acoustic factors such as situational context, soundscape, and how the visibility of drones affects annoyance from their noise are not well studied, and there is a knowledge gap around the effects of drone noise on humans, and subsequently how policy and legislation should be developed to minimise adverse effects on people.

7.6 **Torija and Nichols** investigated the metrics most suitable for assessing the human response to drone noise. A subjective experiment was undertaken to gather data on the human response to a set of drone sounds, and to investigate the relationship between perceived annoyance, perceived loudness and perceived pitch and key psychoacoustic factors. This was an online experiment, where participants (N=49) interacted with an online interface and were required to provide responses to 44 individual drone sounds, with a focus on perceived annoyance, loudness, and pitch. Participants used a set of sliders to prove their responses to the drone sounds presented. The authors explained that the reason perceived loudness was chosen as an outcome was because it is assumed to be a suitable response metric for explaining the effect of the distance of drone operation on perceived response. Perceived pitch was chosen as it is assumed to be a suitable response metric for explaining the effect of drone noise frequency content on perception.

7.7 The multi-dimensional scaling technique (MDS) was used in the study. A continuous scale (from 0 to 1) was used for each subjective variable, labelled: ‘Not Annoying’ at the left end and ‘Highly Annoying’ at the right end (perceived annoyance); ‘Not Loud’ to ‘Highly Loud’ (perceived loudness); and ‘Low Pitch’ to ‘High Pitch’ (perceived pitch). Annoyance, loudness, and pitch were analysed along with the height of the drone above ground level (HAGL). The relationship between annoyance and height above ground level is shown in Figure 3.

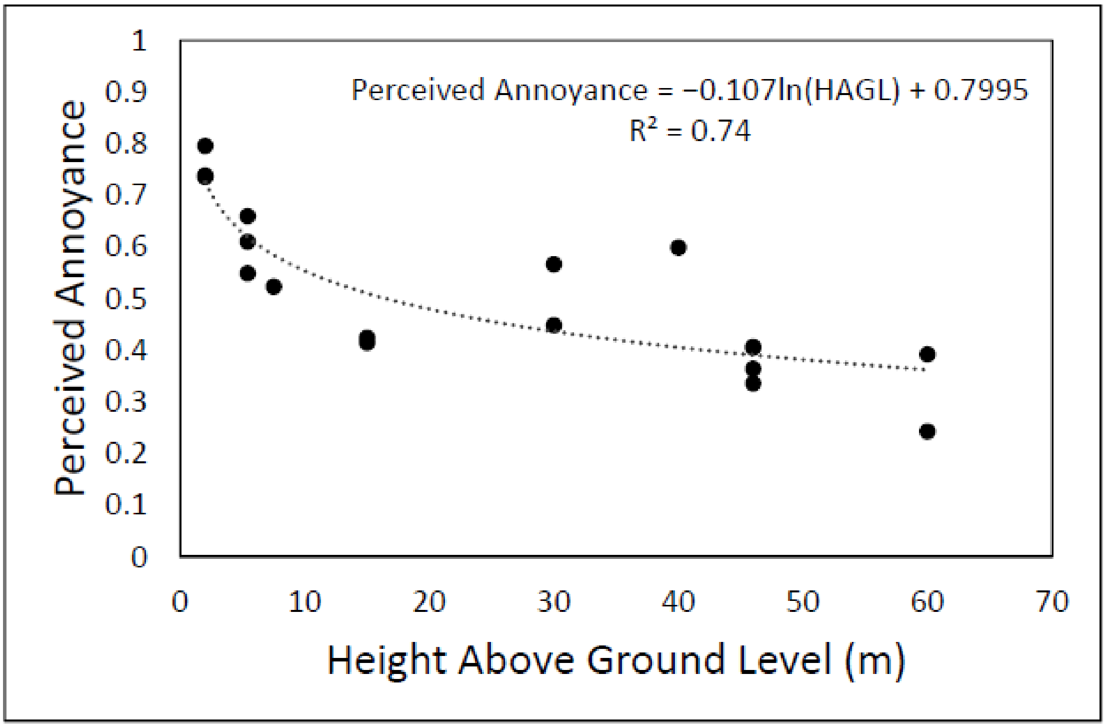

Figure 3: Perceived annoyance versus height above ground level of the UAS during flyover.

7.8 The relationships between perceived loudness and perceived pitch and height above ground level showed similar trends to the one seen for perceived annoyance. The authors explain that the perceived loudness decays more rapidly with HAGL than the perceived annoyance, which they suggest may be due to psychoacoustic factors (and probably non-acoustic factors, such as perceived safety) other than loudness.

7.9 Further investigation suggested that perceived annoyance was mainly influenced by Perceived Noise Level (PNL) and sharpness, which the authors explained confirmed the significance of the high-frequency content present in drone noise. For perceived loudness, participants' responses were mainly driven by PNL and fluctuation strength. Perceived pitch was found to be highly influenced by sharpness, tonality, and roughness.

7.10 The authors concluded that further research on the effects of drone noise on soundscapes, how ambient noise may mask drone noise, and the influence of noise masking on the perception of drone operations is required.

Chapter 8
Summary

8.1 This report has provided an overview of the current state of knowledge concerning eVTOL aircraft noise and the potential effects on people. It has summarised the main findings presented at the Internoise and Quiet Drones conferences held over the past few years, and other relevant publications.

8.2 A growing area of research, studies into the effects of this type of noise include the development of exposure-response relationships for annoyance and perceptions of noise characteristics. The impact on sleep disturbance will need to be understood more clearly, as well as the role non-acoustic factors will play with this type of noise exposure and response. It is expected that findings from more studies into the effects of eVTOL vehicle noise will be seen at upcoming conferences, and this area will prove to be important for developing noise policy and legislation for these kinds of aircraft, and for the protection of the people exposed to noise from them.

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