Report

Noise from drones

M+P.BAFU.22.01.2 (final) | 12 September 2024

Colophon

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Members of the IGNA that endorse this report are the Environmental Protection Agencies of the following countries:
Germany (co-chair), Switzerland (co-chair), Norway, The Netherlands, Italy, Denmark, Czech Republic, Slovakia, Austria, Slovenia, Ireland, Malta, Hungary, North Ireland, Luxembourg, and the European Environment Agency

This report is the result of the work of the EPA Network's Interest Group on Noise Abatement. While it reflects the inputs of all participants of the Interest Group, it is only endorsed in this form, including policy recommendations, by those Agencies mentioned above.

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Authors ir. Bert Peeters
ir. Wout Schwanen

Contact ir. Bert Peeters | +31 (0)73-6589050 | info@mp.nl

M+P Wolfskamerweg 47 | NL-5262 ES Vught
Visserstraat 50 | NL-1431 GJ Aalsmeer

www.mplusp.eu | part of Müller-BBM group | member of NLingenieurs | ISO 9001 certified

Summary

Unmanned aircraft, commonly referred to as ‘drones’, are an emerging new form of mobility that is expected to rise quickly. And with that comes a potential future noise and health problem. This report provides an up-to-date overview of noise from drones and urban air mobility, including technology, acoustics and regulations, based on literature review. It is aimed at a broader audience, serving as a first read into the topic of drone noise. Also, it explains why a new noise and health problem may indeed be expected from this development, and provides recommendations for various stakeholders to prevent this. This report focuses on civil use of drones, mainly for transport purposes, and does not cover military drones and applications.

Current drones are typically suitable for short-distance (< 100 km) and low-weight (< 200 kg) transport of goods and soon also people, as well as for surveillance and inspection purposes. For delivery of packages and surveillance, drones are already in use, albeit in very small numbers currently. Urban air mobility is expected to increase rapidly in the next few years. It is seen by both industries and governments as a fast, safe and sustainable means of transport that will replace or add on to land-based transport, especially for shorter distances and last-mile deliveries. Use cases include public services, such as medical or emergency transport, surveillance and inspection, but also commercial delivery of goods, such as for shopping and food delivery. First commercial operations of passenger transport by drones (air taxis) are expected by 2025. It may be expected that all Europeans will start seeing and hearing drones regularly in their living area before 2030.

Drones have a distinctive and unusual sound, depending on the model and type, that is shown to be more annoying than other transport sounds, including aircraft noise. Many drones use propellors that make tonal, buzzing or whining sounds that capture people’s attention. The fact that the sound is currently unfamiliar, added to people’s worries about safety and privacy, is an important factor for annoyance and related health impacts depending on the use case. Research shows that noise and environmental problems, including wildlife, are people’s top concerns, although their general attitude towards urban air mobility is positive.

Regulations for drones exist on an EU level, both for type approval of the drones themselves and for the operators and operations, which contain some aspects of noise. Current type approval regulations provide sound power level limits for certain categories of drones, and specific measurement methods have recently been developed. For drone operations, regulations state that operators and pilots should avoid causing annoyance or impact nature, but without quantitative or SMART guidance. In general, it is the responsibility of local authorities to decide where and when drones are allowed to operate, within their local ‘U-space’. As with regular aircraft, noise measures are primarily taken at the source or in the form of routing and operational restrictions.

It is concluded that due to the expected rise of urban air mobility, combined with the acoustic characteristics of drones, there are justifiable concerns about their considerable future impact on noise and health. Even though there are undeniably positive aspects to drones, in terms of economic development, sustainability and benefits from societal applications, this negative impact of drone noise to public health seems to be underrated.

This report provides several recommendations for EU institutions, including the Commission and EASA, for the drone industry as well as for acousticians and noise and health experts. The main recommendations are the following:

- Noise from drones should be regarded as a serious threat to future public health and well-being. Governmental authorities as well as the drone industry should start discussing and communicating it as such, rather than a mere issue of societal acceptance.

- The Commission should consider and communicate noise from drone transport to be included their definition of ‘transport noise’, as meant in the Zero Pollution Action Plan ambition to *reduce the share of people chronically disturbed by transport noise by 30%*. Development of a noise assessment method to enable inclusion of drone transport noise in the END noise maps needs to continue. Given the acoustic and non-acoustic characteristics of drones, existing exposure-response functions should be considered to be inadequate and updated or expanded for drone noise. Broadband time-average indicators such as L_{den}, L_{night} may not be representative for the particular sound and psychoacoustic indicators (tonality, roughness, sharpness) could be required. Alternatively, penalty factors for tonality or other acoustic characteristics, like those existing for other noise sources, may be considered.
- Cities and local governments should be aware of their key role in the future of drone mobility, as they will need to decide and justify where and when drones may operate within their local airspace. They should familiarise themselves with the topic of drones and start thinking and discussing about local policy. They may expect requests for permissions to operate from drone service providers, as well as requests for prohibiting this from residents. Local citizens must be involved in decisions on where to locate vertiports, how to route drone traffic through the city, and more generally on the trade-off between opportunities and risks for urban air mobility. It would be effective for cities to work together with other cities, as well as with environmental protection agencies and national authorities.
- Current drone (noise) regulations need to be regularly reviewed and updated as the real issues, including complaints, annoyance and health problems, will start to arise only after the number of drones has already increased beyond a point of no return.
- Further research should be done by acoustic and drone experts together, and stimulated and facilitated by EU and other governments. This includes also research into spatial planning and routing, as well as effective operational boundaries.
- The drone industry and service providers need to be aware of this potential future noise and health problem, should be open to discussion and work together with the noise and health community to prevent this, to develop a long-term stable and sustainable sector.
- Environmental acousticians and health experts must be open for discussion and cooperation with government and industry stakeholders and take an active position, to ensure that they are all well informed and aware of the emerging potential health problem, and actively seeking to prevent this.

Contents

List of abbreviations

AAM	Advanced Air Mobility
BPF	Blade Passing Frequency
BVLOS	Beyond Visual Line Of Sight
EASA	European Union Aviation Safety Agency
END	Environmental Noise Directive
EPA	Environmental Protection Agency
EPNL	Effective Perceived Noise Level, measured in EPNdB
EU	European Union
eVTOL	Electric Vertical Take-Off and Landing
GDPR	General Data Protection Regulation
HAGL	Height Above Ground Level
IAM	Innovative Air Mobility
ICAO	International Civil Aviation Organization
IGNA	Interest Group on Noise Abatement
MTOM	Maximum Take-Off Mass
RPAS	Remotely Piloted Aircraft System(s)
SEL(A)	A-weighted Sound Exposure Level
UA	Unmanned Aircraft
UAM	Urban Air Mobility
UAS	Unmanned Aircraft System(s)
UAV	Unmanned Aerial Vehicle
VLOS	Visual Line Of Sight
VR	Virtual Reality
VTOL	Vertical Take-Off and Landing
ZPAP	Zero Pollution Action Plan

1 Introduction

1.1 Interest Group on Noise Abatement

The EPA Network is an informal grouping bringing together the directors of environment protection agencies across Europe. The network exchanges views and experiences on issues of common interest to organisations involved in the practical day-to-day implementation of environmental policy. In the September 2010 EPA-Network meeting in Krakow the Interest Group on Traffic Noise Abatement (IGNA) was created. In 2017 its mandate was renewed for 2017-2022 at the EPA plenary meeting in Rome, thereby enlarging the scope of IGNA activities to all noise issues, rather than only traffic noise. In 2022 the mandate was again renewed for 2023-2027 at the EPA plenary meeting in Bucharest.

In general, the following objectives are pursued:

- Updating and deepening noise abatement topics from all noise sources as well as quiet areas and summarizing the findings in reports.
- Establish expert opinions on specific technical, regulatory or policy issues and, if necessary, propose statements of the EPA-Network on specific topics.
- Informing EU-institutions and experts.

The group provides an important and valuable platform for the exchange of information on current and future developments, an opportunity to learn from each other, particularly in relation to the development of the regulatory framework and scientific understanding of the issues. The outcomes are practical reports on specific topics containing concrete and helpful recommendations for member states to successfully carry out noise protection.

The key activities of IGNA will focus on recommendations for short and long term objectives, mainly to the following issues:

- Harmonization of noise-monitoring: harmonization and standardization of methods for monitoring and evaluation of noise exposure and remedial measures;
- Noise abatement measures at source and quiet areas: Information and exchange of successful measures to limit noise at sources and to protect quiet areas; exchange knowledge on action plans with stringent regulatory and incentive measures at sources such as for vehicles and machines;
- Critical levels: harmonized critical levels (limit values) that trigger specific remedial measures;
- Economical instruments: cost-benefit aspects and application of financial instruments in order to compensate external costs and to set incentives for measures at sources.

1.2 Motivation and goal

Unmanned aircraft (UA), also ‘unmanned aerial vehicles’ (UAV) and commonly referred to as ‘drones’, have been developed for military purposes in the 1980s and 1990s, and are now a common military tool or weapon. With further development of battery technology, drones are now also available at reasonable cost for industrial and commercial purposes or entertainment. UA are part of unmanned aircraft systems (UAS), which also include ground control and communication systems. Professional, high-end commercial drones are now used for delivery of goods and the first commercial passenger transport services are to be launched in 2025. Drones are promoted by both industry and governments, as they are regarded as a fast, efficient and sustainable means of transport, that may relieve or add onto existing ground transport modes in urban areas.

Drones are also, however, a potential future noise problem. The characteristics of these vehicles, using mostly propellers for propulsion, lead to a particular distinctive sound that people are likely to notice and potentially disturbed by. In terms of their sound power levels, drones may not be very loud compared to other vehicles (airplanes, road vehicles, trains) but as they fly relatively close to people and houses, the sound immission levels at receiver positions can be significant. Additionally, the particular acoustic features, combined with non-acoustic factors related to privacy and safety concerns, may negatively impact the dose-response functions. This will require adequate measures to prevent annoyance, sleep disturbance and other health impacts. Source measures will be needed, i.e. lower sound power levels and less intrusive sound quality, perhaps low noise take-off and landing procedures, optimizing flight paths to prevent flying in noise-sensitive areas, and introducing no-fly zones and/or times.

The scope of this report is limited to civil use of drones. Military drones are not covered, even though people's perception and attitude towards drones is likely to be influenced by associations with military drone use, as they read and hear about this in the news from the ongoing war in Ukraine as well as from other military conflicts. Also, increased activities may lead to increased noise impacts around military drone training fields.
The report focuses mainly on drone transport, although other use cases are also mentioned. It is expected that the most important activity of drones in urban areas that may lead to noise issues will be transport of goods and people from A to B in and around urban areas. Other applications such as remote inspections, surveillance and agriculture are expected to be lower in number and/or further away from densely populated areas.

With the development of this relatively new form of transport comes also the development of adequate regulations. From the noise and health perspective, it is important that such regulations include noise limits and other measures, to prevent the introduction of a new future health problem. For introduction, Episode 11 of the podcast The Rest Is Just Noise[1] is also recommended, which is entitled *Mechanical Birds - Drones and Soundscapes* and features Dr. Antonio Torija, drone noise researcher at Salford University (UK), see https://www.justnoisepod.com/1438372/9315022.

It is the goal of this report:
- to explore and describe urban air mobility in order to better inform acousticians and noise experts about the new technologies and the ongoing developments;
- to investigate to what extent a future noise and health problem could arise;
- to warn stakeholders, being policy makers at all levels as well as the drone industry, about this future problem and to raise awareness;
- to provide recommendations that can help prevent this future problem, and to develop adequate regulations at local and (inter)national levels.

1.3 Definitions

1.3.1 Terminology

Drone is a loosely defined popular term that is used in this report as a synonym for an Unmanned Aircraft System or an Unmanned Aerial Vehicle, see below. In a wider context, a drone can also be an unmanned road or (under)water vehicle.

Unmanned Aircraft (UA) are aircrafts designed to be operated without a pilot or crew onboard. Different types of UA, including propellered VTOL as well as fixed-wing vehicles, are presented below. UA vehicles are almost exclusively electric, although other propulsion types do exist. UA may be flying autonomously or operated by a remote pilot, in which case they may be referred to as

[1] The Rest Is Just Noise (https://www.justnoisepod.com/) is a monthly podcast exploring the relationship between sound and our cities, co-hosted by Dr. Andrew Mitchell, Dr. Francesco Aletta and Dr. Tin Obermann

Remotely Piloted Aerial Vehicles (RPAV). In some documents and online sources, e.g. Wikipedia, the term Unmanned Aerial Vehicle (UAV) is used as a synonym for UA.

Unmanned Aircraft Systems (UAS) are complete systems of unmanned aerial transport that include the UA itself as well as the systems needed for remote control and piloting of the vehicle, such as the ground control system and the system to communicate with the vehicle.

Advanced Air Mobility (AAM) is a new mobility concept for aviation for moving people and goods in cities and regions. Within the scope of this report, AAM involves the use of drones (UA) and air taxis, typically electric and mostly using vertical take-off and landing (VTOL) procedures. Vertiports and other required infrastructure are considered to be part of AAM.

Urban Air Mobility (UAM) is an air transportation system for passengers and cargo in urban environments, enabled by new technologies and integrated into multimodal transportation systems. UAM is a subset of AAM, where AAM includes also regional (intercity) mobility.

Air taxis are small aircraft designed to transport a single or a few passengers over relatively short distances. Although this includes regular flights operating between local airports, using normal, piloted aircraft, the term is used within the scope of this report to refer to electric, mostly VTOL vehicles that can or will soon fly autonomously or remotely piloted. Air taxis are not unmanned and may or may not be included in the definition of ‘drones’. Air taxis are in their early stages and are not yet operational; the info in this report is therefore limited to a few case studies in Chapter 5. Where terms UAS, UA and drone are used further in this report; air taxis are implicitly included unless specifically mentioned.

A vertiport is an area of land or water, or a structure intended to be used for the landing and take-off of VTOL aircraft, specifically for air taxis. Vertiports are expected to appear in in different sizes and numbers in cities, depending on traffic volumes. Small vertiports (*vertipads*) will have one or two landing pads, whereas *vertihubs* can have around ten landing pads.

In this report, the term ‘drone’ will be used as much as possible as the use of abbreviations decreases the readability. It will be clear from the context if the word refers to the UA, to the UAS including other system components, or to UAM as a transport mode. Mostly it will be the UA that is referred to, as the subject of the report is noise and the source of the noise is the flying vehicle itself and its on-board components.

1.3.2 Vehicle categorisation

Aircraft layout
According to a 2021 EASA report [6], UA layouts for vertical take-off and landing can be categorised into three archetypes. Examples of each type are shown in figure 1.

Vectored thrust, also known as *tilt rotors.* The same propulsion units first provide lift during the hover and then swivel to create thrust in the cruise phase. During the cruise phase, lift is generated by the wings. This layout is better suited to longer-distance flights, as the system is more efficient but more complex than the other concepts.

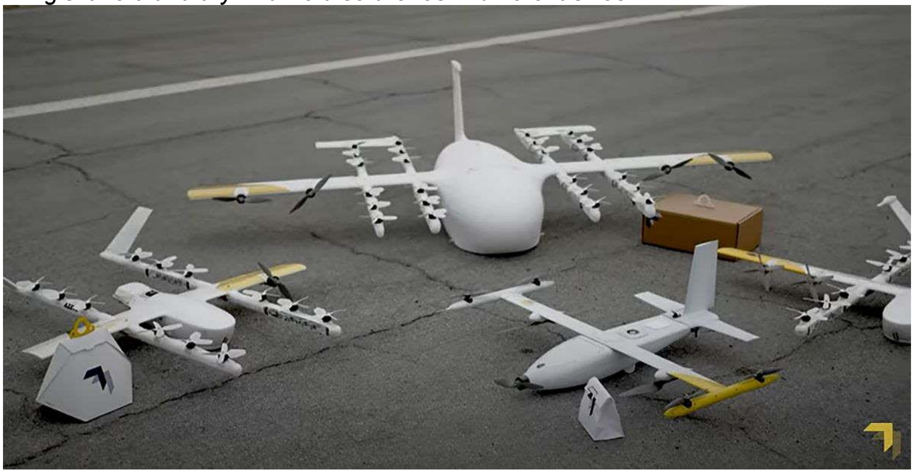
Lift + cruise. This layout has separate propulsion units for the hover and cruise phases. Wings create the necessary lift during the cruise phase. Lift + cruise is suited to shorter distance flights than vectored thrust, but to longer distances than wingless.

Wingless (multicopter). Here the propulsion units are fixed in position and create lift all the time. This is the option that offers the shortest flight distances, as the efficiency is lower, and is a simpler concept than other two types, as it has less movable parts (than e.g. thrust vectoring).

Classic fixed-wing drone models exist that only have forward propulsion and depend on the wings for vertical lift and require some runway for horizontal take-off and landing. Most of the applications considered in this report focus on urban areas where space is limited, or require hovering capabilities for drop-off, imaging, etc. Non-VTOL aircraft is therefore not within the focus of this report.

Wingcopter 178 HL: tilt-rotor / vectored thrust drone

Wing's 'aircraft library': lift + cruise drones in different sizes



DJI FlyCart 30: Multicopter wingless drone

figure 1 *UAM aircraft types for vertical take-off and landing*

Use cases
In literature, the following UAM use cases are found, grouped into different functions [6]:

Passenger transport, mainly the air taxi: in the beginning passengers will use the UA to travel from one vertiport to another but one can imagine that eventually it may be possible to catch an air taxi close from the starting point of the travel in a street or park to the end point of the travel without making use of the vertiports anymore. Another application is quickly flying in an emergency doctor to an accident site.

Delivery. Use cases are the delivery of food and packages by drone to people's homes or backyards, and drones delivering packages into a central delivery hub. Usage of drones can also include time-critical medical applications, like the delivery of lab samples, medication or organ transport.

Civil surveillance and other operations. This includes inspection/maintenance of bridges, powerlines and other infrastructures. An example is the UIC project DRONE4RAIL [40], where European railway infrastructure managers participated to research the use of drones for rail bridge inspections. Other cases include precision agriculture and the preliminary visual assessment of incident sites: one can think of assessing the extent of fires and accidents. And there are other sovereign functions that make use of drones, such as police surveillance or crowd control. Some of these applications are outside the urban airspace and may not be considered UAM.

2 Noise sources and measures

2.1 Acoustical characteristics

Schäffer et al [31] performed a systematic review of the noise emission characteristics of drones. All relevant literature considered so-called multicopter type drones (e.g., like the quadcopter). They observed large differences between all relevant studies in the measurement environment, the number and set-up of the used microphones, the measured quantity and the operating mode of the drones under testing. The variety in test conditions makes it difficult to compare the results. To make the measurement data of the different studies comparable, Schäffer et al introduced one parameter to characterize the acoustic emission: the A-weighted sound pressure level at a distance of 1 m under free-field conditions and at a radiation angle of -30° with respect to the rotor plane, so under and sideways away from the drone. Several transformation and normalization procedures were applied to convert the different measured values into this new parameter. The resulting emission levels were analyzed with respect to mass of the drones and to way of manoeuvring, see figure 2. The sound levels when forward flighting are slightly higher than for hover, about 0 to 3 dB(A) for drone masses up to approximately 5 kg.

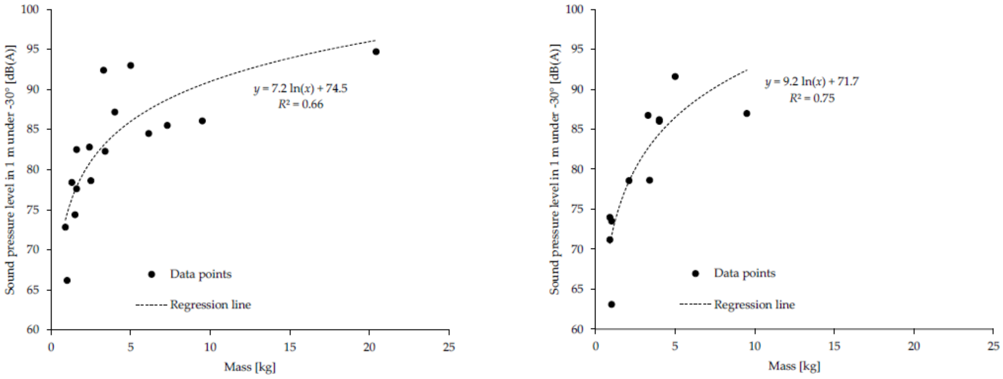


figure 2 *Free-field emission values for multicopters as A-weighted sound pressure level at a distance of 1 m for a radiation angle of -30°, as a function of the drone mass. <u>Left</u>: forward flighting, <u>right</u>: hover [31].*

Two studies provide spectral and angle-dependent information on the source directivity for multicopters. Treichel and Körper [38] present a mean of three different drone models which were measured in outdoor conditions. Heutschi et al. [19] derived a generic spectral directivity from measurements on five different drone models. The drones operated at different rotational speeds in laboratory conditions. Schäffer et al. [31] summarized these results and constructed the figure depicted in figure 3 showing the vertical noise directivity referred to a radiation in the direction of -30° (below the horizon) with respect to the propeller plane. At an elevation angle of 0°, the noise level for the mid and high frequencies is about 4 dB lower and at ± 90° (i.e. straight above or below the propeller plane), the noise level is about 6 dB higher. The directivity effect in the mid and high frequency range between horizontal and vertical radiation direction is thus about 10 dB.

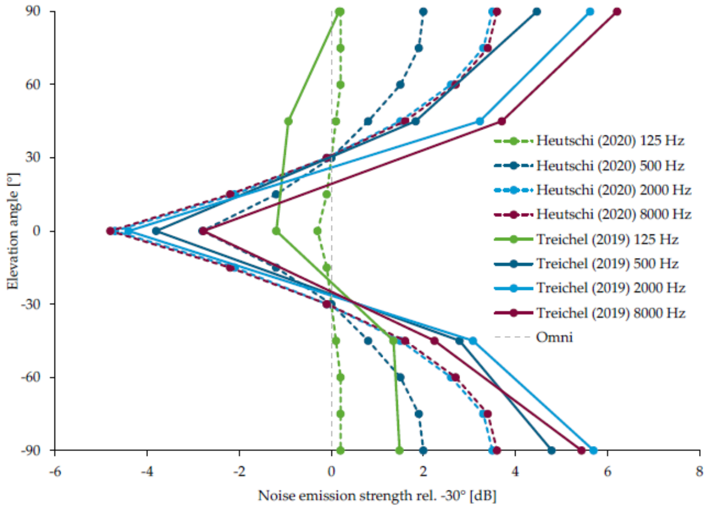


figure 3 *Vertical noise source directivity patterns of multicopters at different frequency bands ([31], data from [19] and [38]).*

Torija et al. [33] took a series of acoustic measurements of a small fixed-pitch quadcopter (DJI Phantom 3 Standard), both in a controlled indoor acoustic environment and while flying outdoors. The test in the controlled indoor acoustic were performed under different conditions: the quadcopter was fixed to a horizontal stand, with only the electric motors working and with one, two and four rotor blades operational. The resulting narrow-band spectra are depicted in figure 4. A significant content in high frequency is observed for the electric motor with clear tones between roughly 2.5 kHz and 6 kHz.
When the propellors are active as well, clear harmonics of the Blade Passing Frequency (BPF) at the low-to-mid frequency region can be determined. For the lower frequency range, the sound levels of the harmonics are almost equal, independent of the number of active propellers. At the higher harmonics of the BPF, the two-propeller condition shows slightly higher sound levels than the condition with only one propeller. The four-propeller condition shows significantly higher sound levels for the higher harmonics of the BPF compared to the single propeller condition).

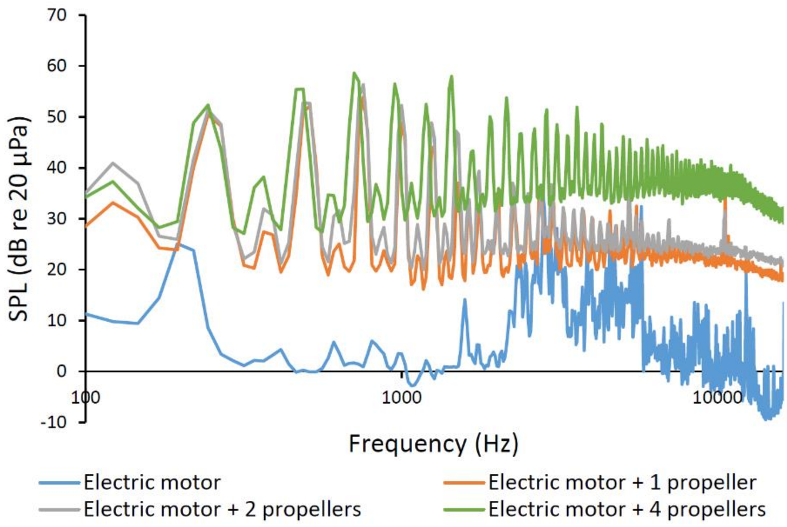


figure 4 *Frequency spectrum of a quadcopter tested under different circumstances: electric motor only, and electric motor with one, two and four propellers. Figure is from reference [33].*

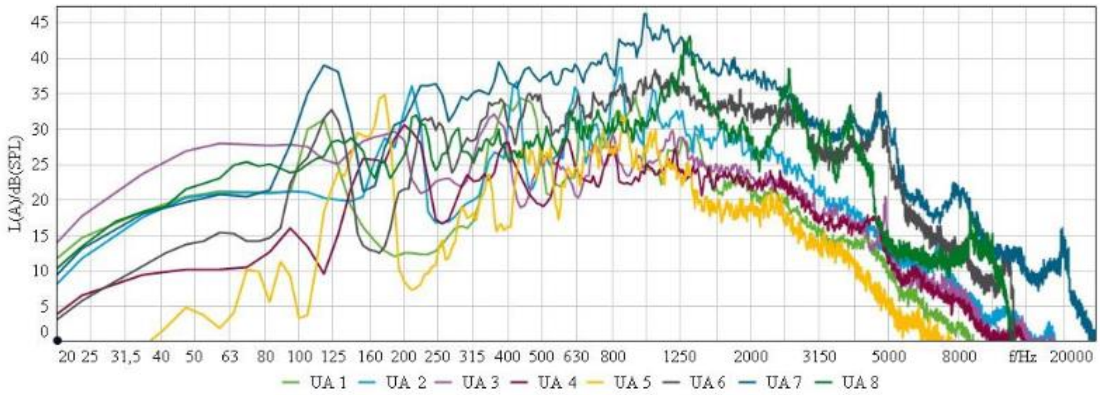


figure 5 *Frequency spectra of five quadrocopters (UA1-5) and three octocopters (UA6-8) measured during outdoor overflight [36]*

Measurement results by Treichel et al. on eight different small to medium sized quad- and octocopter UA models published in 2023 [36] confirm the clear presence of tonal components in the spectrum related to the BPF as well as a relatively high frequency content (sharpness), see figure 5. Further analysis of psychoacoustic indicators is given in a 2024 conference paper [37], showing that the loudness and sharpness of the drone sound also depends on the operational mode, indicating that optimization of the flight manoeuvre may also lead to lower disturbance. Fast overflights at high altitudes are preferred. The authors also recommend that psychoacoustic metrics are used, at least supplementary, to adequately quantify drone noise in regulatory noise assessments.

Unsteady force noise that occurs on a periodic basis, for example from disturbed inflow due to other rotors or the fuselage, is an important source of noise at higher harmonics of the blade passage frequency. An example is given in the figure below where a spectrogram of a hovering drone in the laboratory and outdoors is given [33]. The BPFs of each propeller are near 175 Hz for the outdoor measured drone whereas the BPFs of each propeller are around 250 Hz for the quadcopter measured in the laboratory. The drone shows an unsteady frequency behaviour with time outside. In comparison with the spectrogram measured inside, the drone hover shows distinct spectral lines at harmonics of the propeller BPFs. Both the frequency variations with time and the distinction of spectral lines are magnified at higher harmonics. Under hover condition outdoors, wind gusts and the flight control system varying rotor rotational speeds to maintain vehicle stability create such an unsteady acoustic signature. These results confirm earlier findings of Cabell et al [5].

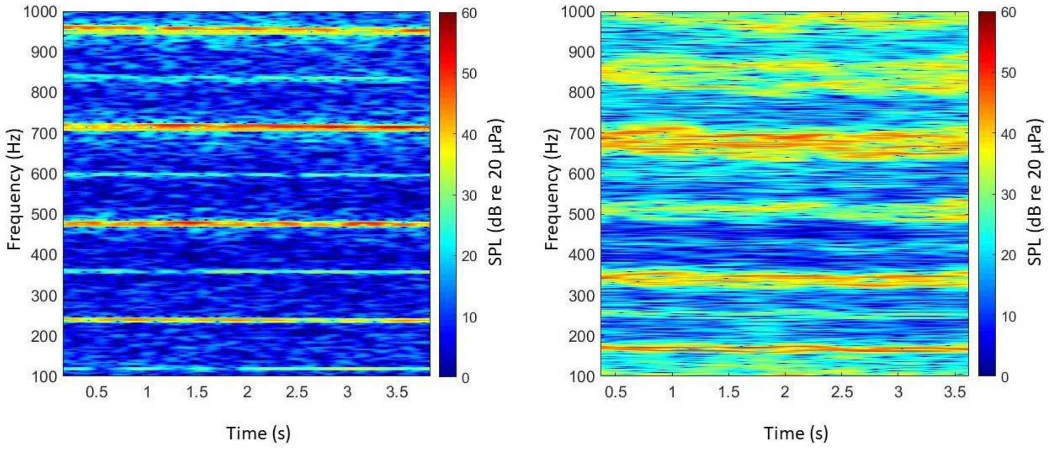


figure 6 *Spectrogram of a hovering drone measured in the laboratory (left) and outdoors (right) [33].*

2.2 Annoyance and other health effects

The studies found in literature only focus on short term effect of drones. No studies are yet available on long term effects of drones on humans. Nevertheless, the available literature shows good resemblance in the results. First, drone annoyance strongly depends on the sound level: the higher the sound level, the higher the annoyance. Drone noise does not differ from other transportation noise sources in that regard [20]. Secondly, literature indicates that done is considered more annoying than road traffic noise or aircraft noise. This paragraph describes several research results from recent years focusing on noise annoyance from drones, psychoacoustic indicators used to describe this, and differences in annoyance between drone types, operations and between drones and other transport modes.

It is suggested that drone noise annoyance highly depends on metrics that are loudness related. Schäffer et al. [31] mention pure tones (tonality) and high-frequency broadband noise (sharpness) as important additional reasons for the increased drone noise annoyance. The drone noise spectrum shown in figure 9 clearly shows a higher high frequency content as well as tonal components (visible as peaks in the spectrum). Torija et al [33] observe that the high frequency contribution in the drone noise is clearly higher than for aircrafts and road vehicles. They conclude that the observed difference in high frequency content between the vehicles tested is well represented by the sharpness metric. In [26], it is indicated that the drones also exhibit a relatively high amount of roughness, i.e. rapid fluctuations of the amplitude over time.
Due to the higher loudness, sharpness and tonality of the quadcopter, the calculated psychoacoustic annoyance is also higher than for the aircraft and road vehicles under testing [33][36].

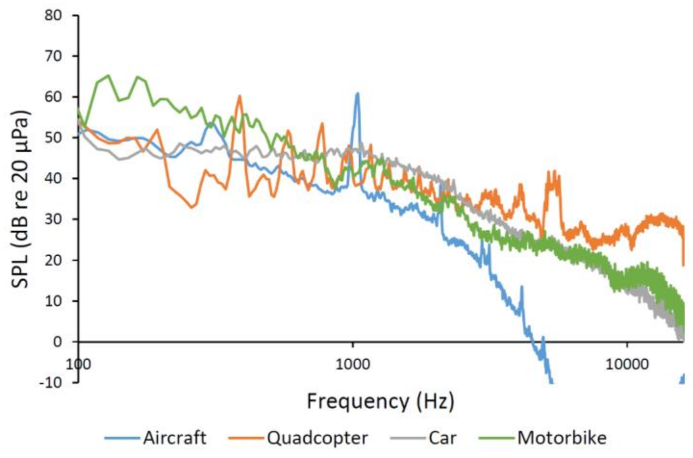


figure 7 *Frequency spectrum of a quadcopter compared to other traffic noise sources (figure from [33]).*

In a 2022 study Torija et Nicholls [34] researched the noise perception of drone noises for different flying operations, size, weight and distance from the receiver. The response variables in the study were perceived annoyance, perceived loudness and perceived pitch. Perceived loudness was chosen as it is assumed to be a suitable response metric for explaining the effect of the distance of drone operation on perceived response. The 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. The responses show that the perceived annoyance was mainly determined by the perceived noise level and the sharpness of the signal. This confirms the importance of the high frequency noise of the drones. The perceived loudness is mainly determined by the perceived noise level and the fluctuation strength. In this case, the beating effect due to rotor interactions might affect the perception of loudness. Perceived pitch was found to be highly influenced by sharpness, tonality and roughness. This is most likely explained by the high-frequency and tonal content along with the rapid amplitude modulation due to the unsteadiness of the sound signal.

Aalmoes and Sieben [1] in a 2022 study evaluated the human perception and noise annoyance of drones in a VR simulation environment, for hovering as well as fly-over events. One of their conclusions is that hovering sounds are perceived as more annoying than fly-overs at the same sound exposure level. They also found that the visual perception of the drone seemed to have a smaller influence on the perceived annoyance than what was expected, and that the presence of higher or lower levels of background sounds also had little influence. The fact that people are unfamiliar with drone sounds is stated to negatively influence their perception, as well as their general attitude towards drones and their expected societal function.

In another VR lab study for EASA [7] Aalmoes et al. derived dose-response curves for a small number of different drones, an air taxi and, for reference, two helicopters and a small fixed-wing aircraft. For each vehicle, fly-over sounds were presented to participants using headphones, without visual stimuli. The study included 40 participants, who reported their annoyance for the different sounds on an 11-point scale. As with other environmental noise sources, reported annoyance was higher with increased noise levels (A-weighted sound exposure levels), see figure 8. It should be noted that this dose-response function is not comparable to the established WHO exposure-response functions for other noise sources, as they are based on a small scale laboratory experiment and also because the dose metric is an A-weighted SEL rather than a L_{den} level.

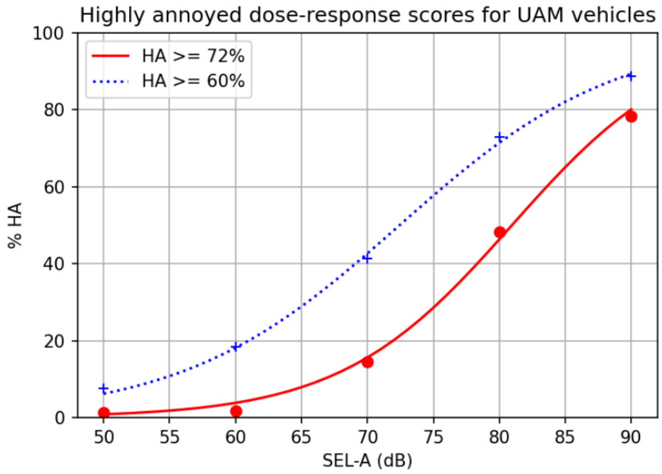


figure 8 *Dose-response curve found from EASA laboratory listening experiment, representing the average curve for several VTOL drones, a fixed-wing electric aircraft and an air taxi [7]*

Dose-response curves, see [7], show higher annoyance for the drones and the air taxis than for the helicopters. Unfamiliarity with drone sounds is mentioned by the authors as a possible explanation, but this has not been examined. The review by Lotinga et al. [26] summarizes from various sources that UA sounds are more annoying than conventional aircraft with a difference equivalent to an increase of 5 – 10 dB in A-weighted sound level, and 4 – 7 dB more annoying than road traffic noise.

A 2024 study by Salford University [18] compared the perceived annoyance of three types of drone sounds against three types of regular aircraft sound. Sound recordings were presented to a test panel at the same loudness level. The drones included different drone sizes including a Malloy T150 large 'heavy lift' drone. They found that for some drone-aircraft comparisons the drone was more annoying than the aircraft, possibly related to the higher sharpness of the drone sound as well as a more sudden rise and fall of the sound. For other drone-aircraft comparisons, the drone sound was considered less annoying than the aircraft, e.g. when comparing the T150 drone to an Airbus A320. The authors explain this by indicating the higher tonality and roughness of the Airbus sound, whereas the heavy T150 has a relatively steady sound (low roughness) with low tonality.
A 2024 study by the Swiss EMPA [23] indicated that a smaller drone was more annoying than a heavy drone, at comparable sound exposure levels. The study also confirmed that vertical manoeuvres (take-off and landing) are more annoying than horizontal fly-overs.

A 2024 study by Aalmoes and Sieben [2] in a Virtual Reality environment combining audio as well as visual stimuli fly over events indicated that the sound of a DJI Matrice 600 hexacopter drone was perceived less loud and less annoying than the sound of a Boeing 737, at least in a rural background environment. The authors indicate that the sounds were equalized in volume based on the L_{max} level, but that the Boeing did have a higher SEL as well as a higher EPNL level, which could possibly explain the observed difference.

In general, we can conclude from the literature that the perceived annoyance depends on loudness related metrics, but the specific, atypical spectral content and time fluctuations of drone noise make other acoustic indicators, such as sharpness, tonality and roughness, indispensable. For regulations, adding additional indicators to existing metrics (L_{den} / L_{night} or EPNL) is likely to be unfeasible as it would make noise calculations and limit values much more complex. An alternative could be to introduce penalty factors to the existing metrics for tonal sounds, or other sound characteristics that increase annoyance. Standardised methods for tonality, such as the ISO1996-

2:2017 or ISO/TS 20065:2022 are available. Some information on penalty factors in national noise regulations was provided in an earlier IGNA report, see [30] section 4.2.5.

Non-acoustical factors also play an important role in the drone annoyance, potentially even more so than for conventionally aircraft. The unfamiliarity with drones in general, the perceived potential danger for people and birds and concerns about privacy violations by the drone's camera are examples of psychological factors that may lead to increased annoyance. Also, conscious or unconscious association with war drones could lead to higher negative response.

2.2.1 Influence of distance from drone on annoyance

Torija and Nicholls [34] found a good correlation between the responses and the distance between drone and receiver, the latter being expressed as the Height Above Ground Level (HAGL). An increase of HAGL for drones flying over resulted in reductions in perceived annoyance, perceived loudness and, to a lesser degree, perceived pitch. However, the perceived loudness declines more rapidly than perceived annoyance for increasing HAGL. The results are summarized in figure 9.

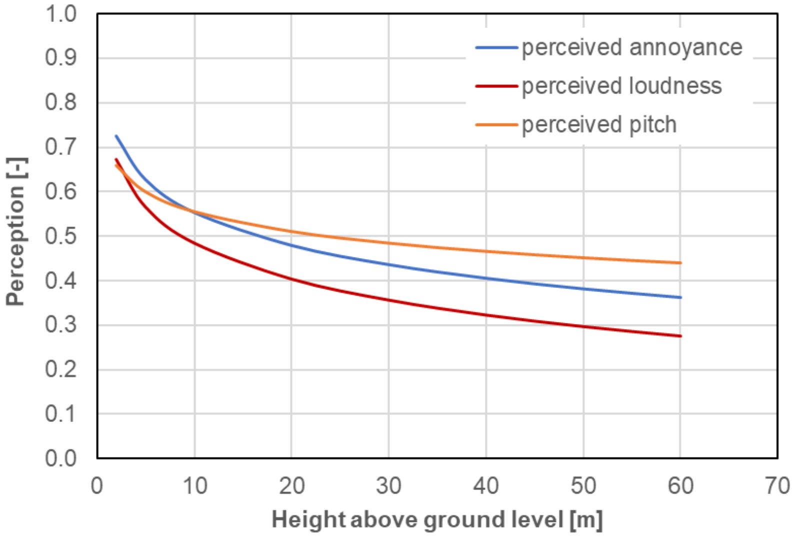


figure 9 *Perception of drone noise, expressed as perceived annoyance, perceived loudness and perceived pitch as function of the height above ground level for the drone in flyover (Data from [34]).*

As pointed out in [26], drones fly over relatively close and therefore atmospheric absorption is relatively low, contributing to a higher high frequency content at the receiver compared to conventional aircraft. Also, the rise and fall times for a nearby drone flyover are much shorter than for normal aircraft, leading to more sudden and unexpected audio events resulting in increased perceptional impact. However, for hovering or during take-off and landing, which is when the drones will be closest to people, this is not the case.

2.2.2 Effects of drone noise on wildlife

The noise from drones may be a particular point of concern with respect to birds and other animals in nature and quiet areas. While such areas are typically protected from ground-based noise sources (road and rail traffic) by natural boundaries, drones have a higher degree of freedom and can more easily surpass such boundaries. Also, the noise characteristics of drones, with relatively high frequency content and tonal components, may be more disturbing for animals as they interfere with their communication. A 2020 EEA briefing[2] mentions the threat to wildlife as a key concern related to drones, citing several sources of evidence. Besides noise, visual disturbance is part of these concerns, as well as the risk of accidents, e.g. birds being hit by drones or mistaking them for food. To give some guidance, a correspondence from the biological field research community mentions several best practices aimed towards those who use drone flights for field research in nature areas [20].

2.3 Measurement of drone noise

EU Regulation 2019/945 details a noise test code for the determination of the A-weighted sound power levels of Unmanned Aircraft classes 1, 2, 3, 5 and 6 for the open category. It refers to ISO 3744:2010 [21] as the measurement method that shall be used, with a set of supplements. The ISO 3744:2010 actually describes a method that generally applies to sound power levels of any product or installation, including outdoor equipment, larger industrial installations and road vehicles (e.g. garbage collection trucks). It is mainly used for stationary or slowly moving sound sources. The method is not directly applicable and requires some interpretation and approximation for it to be usable for UA noise measurements, see [35].
The 2019/945 regulation considers UAS with a maximum take-off mass up to 25 kg. The test code measures sound power levels indoors and outdoors, but the measurement is limited to hovering UAS only.

Technical Committee ISO/TC 20 Subcommittee has been working on a draft ISO-standard specifically for noise measurements on unmanned aircraft systems, which has recently (January 2024) been published as ISO 5305 [22]. This document specifies noise measurement methods for multirotor-powered UAS with a MTOM up to 150 kg. It provides procedures for performing noise measurements during typical UAS flight phases. This includes hover, take-off, landing, and cruise. The standard will specify various microphone configurations to ensure that noise measurements are carried out at different location allowing quantification of the directivity of UAS noise.

EASA published guidelines for determining the noise emission of UAS, that are lighter than 600 kg, and that operate the specific category [9]. The noise measurement method can be applied on various UA designs and caters for two procedures: a level-flight measurement, and for designs allowing a stationary flight, a hover flight measurement. According to ESA, the guidelines intend to close the gap relating to noise measurement standards in the ‘specific’ category. In a 2024 conference paper [27] EASA explains that they did consider adopting the ISO 3744 and ISO 5305 methods, but found these inadequate for several reasons. For the ISO 5305, these include the fact that a suitable noise metric representing the annoyance was not provided, the unproportionate costs associated with the method as well as too many aspects of the measurement being unaddressed. The same EASA paper shows based on a 2020/’21 VR perception study, the EPNL metric commonly used in regular aircraft noise certifications is also the noise metric that correlates best with drone annoyance. As the A-weighted SEL level scores almost equally high and is much more practical to obtain from measurements, EASA selected the SEL(A) as the metric used for their further work including the dose-response functions, see figure 8.

In the review publication by Lotinga et al. [26], many laboratory and field noise measurement campaigns performed in recent years (2016+) are listed and summarized. As these authors point out, laboratory measurements under controlled conditions are accurate but can only be performed on limited operational modes, e.g. when hovering or rotating (‘yaw’) on a fixed position. Wind tunnels could be used to test outdoor wind scenarios, but only under vary low background levels. For flyover, landing and take-off operations and procedures, outdoor field measurements are

[2] https://www.eea.europa.eu/publications/delivery-drones-and-the-environment

required. More and more experience with such methods is being gained internationally, as described in the review.

Wunderli et al. [42] showed that the directivity pattern is widely independent of the rotational speed of the rotors and of the flight procedure. Consequently, the directivity pattern can be determined for a stationary hover flight, which considerably simplifies the measurement procedure. In addition, they showed that the sound power spectrum depends on the rotational speed only: after normalizing the measurement frequencies to a reference RPM value, the spectral shape of the sound power is constant. This makes the emission modelling simpler. The authors show good agreement between their flyover noise measurements and the sound immission over time predicted by their SonAIR model.

2.4 Noise measures

2.4.1 Measures at the source

Research to lower the noise of drones mainly aims at lowering the noise of the blades. The noise of the propeller can be lowered under identical lift generation by lowering the rotation speed. Enhancing the lift coefficient coefficient (lift normalized by reference area and speed) is thus a promising technique for improving propeller acoustic performance. For the design of the propellors, researched are inspired by owls. The particular morphological properties of owl feathers, such as leading-edge serrations, trailing-edge fringes, and velvet surface, are the key to reduction of the noise from the wings [28], [29].
An innovative tech start-up, Undefined Technologies from Florida, is working on silent drone technology that uses ion propulsion, a technique from the spacecraft sector that creates thrust by accelerating ions using electric energy, but previously incapable of overcoming gravity. Figure 10 shows their vehicle. This technology is still in the research phase.

figure 10 The Silent Ventus^{TM} quiet drone by Undefined Technologies (source: https://www.undefinedtechnologies.com/)

2.4.2 Other noise measures

Besides source measures, lowering the impact on the environment is mainly achieved by routing and spatial measures. Propagation measures such as noise barriers are not suitable; façade insulation could in principle be applied, e.g. near vertiports. From that point of the view there is a clear parallel with noise from airplanes.

Examples of spatial noise measures are the strategic urban planning of vertiport locations and location of training fields for drones. An example in Czech Republic shows the importance of the latter where trainings (drone testing, flying around) have been provided at an old disused, small-town airfield which have caused noise problems in neighbouring houses.
Also, establishment of a non-flying zones is a noise measure to reduce the noise. Non-flying zones are already in place for other reasons than noise, for instance around airports and military facilities. Figure 11 shows a Dutch map indicating areas where drone flying is or may be prohibited, permanently or temporarily, for reasons of safety (e.g. around airports, military training areas or during firework shows) but also in nature areas. An international website listing such maps for all European countries is available at https://europeandronecompany.com/. Figure 12 shows a similar online map for Germany indicating restricted areas for drone flight. Looking at this map it seems that all residential areas in cities are in principle restricted, meaning that permission is required before they may be overflown.
Denmark published an executive order on supplementary provisions to EU Regulation 2019/947 on rules and procedures for the operation of unmanned aircraft, which takes into account particularly noise-sensitive areas, and it prohibits flying drones over particular noise sensitive areas unless it is necessary to perform the tasks for supervision, maintenance, public monitoring activities or control tasks.

Another noise measure is the routing of drones, choosing flight paths that evade housing and other sensitive areas. Research project such as RefMap (https://www.refmap.eu/) are investigating dynamic flight route optimization, including AI techniques, to optimize between flight duration, distance / energy consumption and noise impact. Another option, like for regular aviation, is to allow usage of drones only during certain periods of the day or the week. For instance, it might not be allowed to use drones during the night period in certain areas to lower the sleep disturbance.

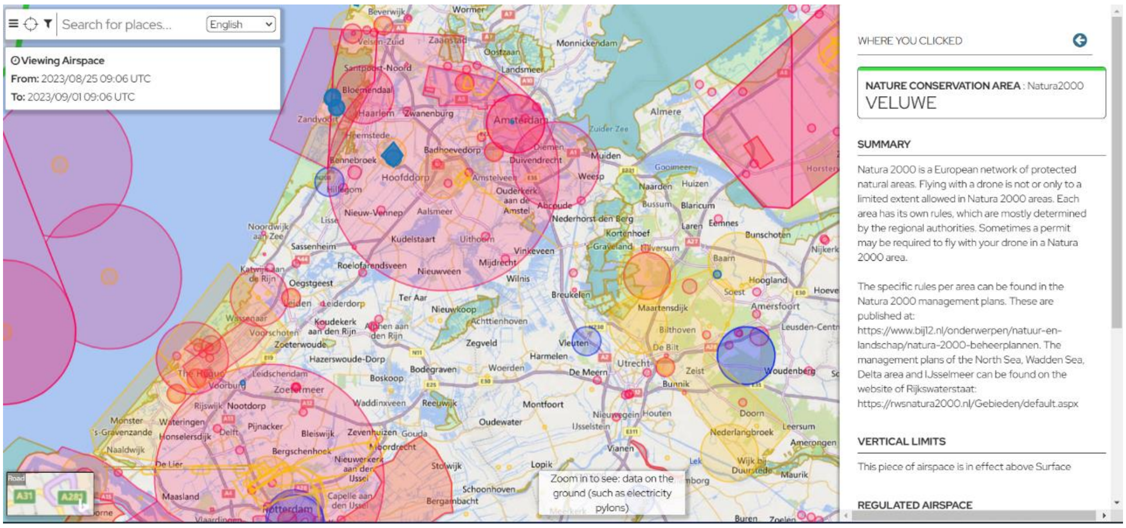


figure 11 *Dutch informative website (https://map.godrone.nl/) showing areas where drone flying may be prohibited permanently or temporarily*

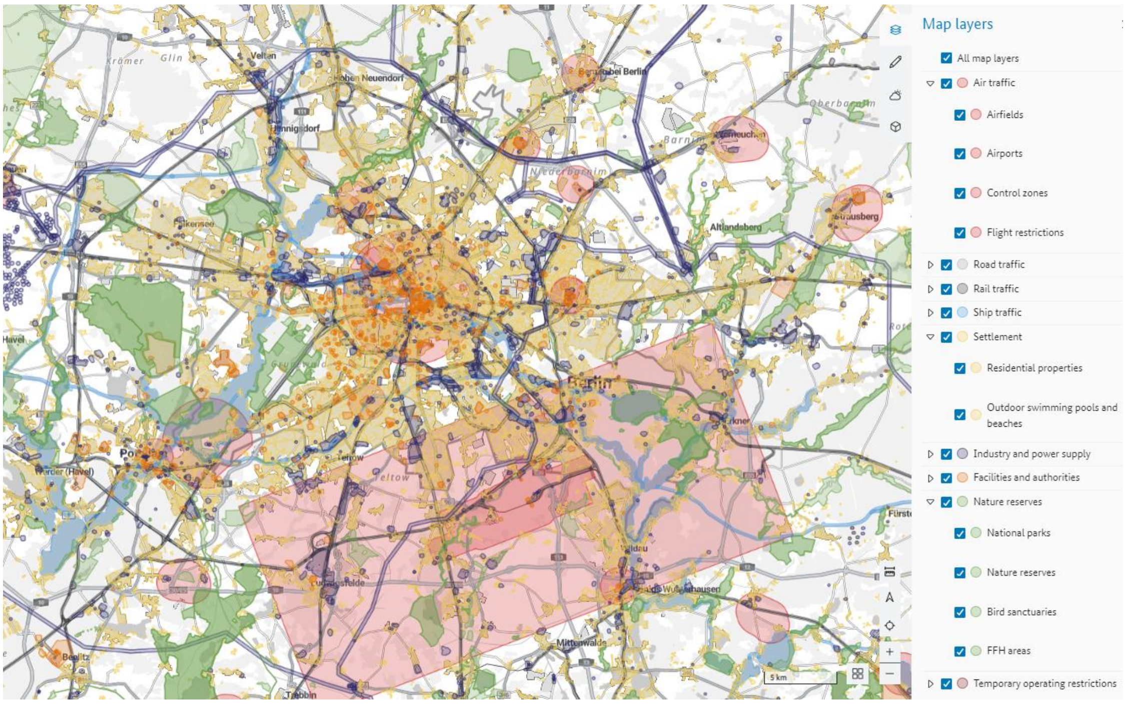


figure 12 *German website (https://maptool-dipul.dfs.de/) showing areas where drone flying is restricted for drones >249 g or drones with video/audio sensors, and requires permission by the Federal State Aviation Authority or the local entity responsible for the overflown area. This screenshot shows the Berlin area.*

3 Policy and regulations

3.1 EU Drone Strategy 2.0

On November 29th 2022, the European Commission adopted the European Drone Strategy 2.0 [17]. This Strategy sets out a vision for the development of the European drone market, and it envisions that drones become a part of European life by 2030 to offer emergency, mapping, surveillance and inspection services as well as passenger transport (air taxis). The Commission has been working on drone policies since 2014 and has been supporting innovation and development by investing close to 1 billion Euros in research and innovation programmes.
Also important in the development of drone traffic is the implementation of "U-Space" in January 2023, which is an EU-wide traffic management system for unmanned aircraft systems. It divides airspace between manned and unmanned flight zones and depends heavily on digital services and standardized communication between all drone service providers and users.

The Drone Strategy is a result of actions set out in the Commission's Sustainable and Smart Mobility Strategy (SSMS, December 2020). The Commission foresees a close future where drones play an important role in European mobility. The development of the drone sector is seen as an opportunity for economic development and jobs, and that the Commission should enable this potential to be unleashed. However, as communicated with the adoption of the Drone Strategy 2.0, "before pushing ahead with these innovative technologies, the Commission wants to ensure that society supports drones. To address concerns over noise, safety and privacy, the Strategy therefore calls for national, regional and local municipalities to ensure that drone services are aligned with citizens' needs"[3].

In the Drone Strategy 2.0 [17], the issue of noise is mentioned and addressed in several places. Relevant statements in the document are the following:

- The Zero Pollution Action Plan [15] is linked within the SSMS with targets and actions on how clean the new EU transport policies should be, for instance on noise and air pollutants.
- Important concerns associated with societal acceptance of UAM were found in the EASA study ([6], see also § 3.2) with noise and safety ranking first. More in-depth follow-up studies on societal acceptance and on the environmental impact of drones should be conducted at European and national levels, broadening the effort already made by EASA, followed by a Working Group with participants from all countries to jointly evaluate possible solutions.
- Local communities, cities and regions have a key role in deciding to what extent drone operations can be conducted in their territories. They are in a good position to assess which critical infrastructure should be protected, whether operations should be allowed in day or night-time, what should the measures in place be in terms of noise and visual abatements. The role of municipalities is also pivotal in terms of regional planning in urban and rural areas and the creation of dedicated infrastructure to accommodating vertiports or take-off and landing sites. The location of such infrastructure in the urban environment should be systematically analysed, finding a balance between location requirements, affordability and other aspects, such as nuisance to neighbours and visual pollution to avoid jeopardising social acceptance.
- Noise mitigation measures to avoid or limit the impact on over-flown citizens, houses, quiet and natural areas should be fully taken into consideration by drone operators and local authorities when designing routes, procedures, and other operational practices.
- EASA should also continue the development of suitable drone and eVTOL noise modelling methodologies, which should be considered by the Commission for the next amendment of Annex II of the Environment Noise Directive for the purposes of adapting common noise assessment methods to scientific and technical progress.

[3] from https://ec.europa.eu/commission/presscorner/detail/en/ip_22_7076

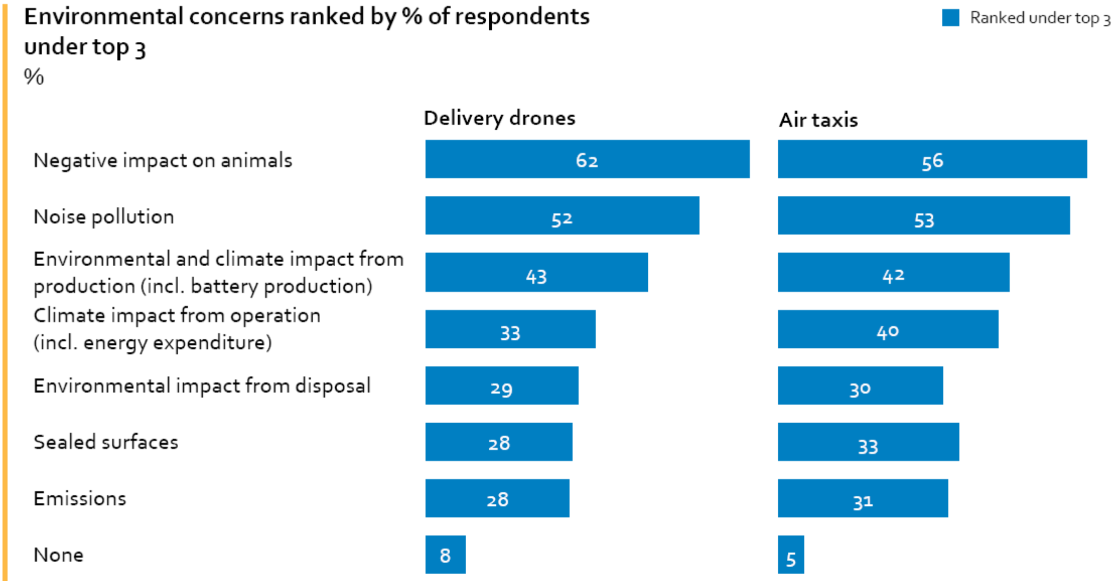
The Drone Strategy concludes that the drone sector that the EU is striving for must be mindful of its environmental impact in terms of noise, energy consumption and visual nuisances in particular. The Commission acknowledges that drones will need to be socially accepted to play their full role for the benefit of businesses and local communities. This will require the full upfront involvement of all parties concerned at local, regional, and national levels to make sure that safe and secure drone operations can be deployed, both in urban and rural areas, in a fair and sustainable manner. To enable this, the Commission intends to fund the creation of an online platform to support a sustainable implementation if innovative air mobility (IAM) by authorities, cities, industry and stakeholders.

3.2 EASA societal acceptance study

The EU Aviation Safety Agency (EASA) commissioned a study to McKinsey & Company to investigate the EU citizens' willingness to accept drones as a new mode of transport, and to identify and quantify their possible concerns and expectations. The study was launched in November 2020 and included a survey with around 4000 residents of six European cities, as well as qualitative interviews with various focus groups and a noise perception study with 20 EU residents. With the results of the study, EASA wants to provide a regulatory framework that will enable this new mode of transport and allow the EU to take a leading worldwide position in this field.

The study is summarized in a 2021 EASA report [6]. Some of the conclusions relevant for noise are the following:

- EU citizens have a positive initial attitude towards unmanned air mobility, which is seen as an attractive transport mode. Use cases for community benefits, such as health care, are better supported than individualistic use cases, such as food delivery.
- People expect drones to be a cleaner, more sustainable and faster alternative to other transport modes. It is seen as a good option to reduce traffic congestion, leading also to improved emergency response time, and to improve local air quality.
- The top-3 of concerns identified by the survey respondents for delivery drones were safety, security and environmental issues, with noise concerns at place six. For air taxis, noise was ranked second, after environmental issues. When asked specifically about environmental consequences, including environmental issues and noise, figure 13 shows that more than half of the respondents mention noise in their top-3 of concerns. Negative effects on wildlife are also considered important. When asked about their concerns if a vertiport would be nearby, take-off and landing noise is the top concern among respondents.
- In summary, the EASA report ranks noise as the second main overall concern.
- The noise perception study was a relatively small study using laboratory audiovisual (VR) stimuli. It showed that people are more annoyed by drone sounds at higher levels, and that they are more annoying than other, more familiar city sounds at the same decibel levels.
- The introduction of drones into existing ground and air infrastructure must respect citizens' quality of life and the cultural heritage of EU cities.



Source: EASA UAM societal acceptance survey questions B9. What are your greatest concerns when it comes to the possible envir onmental consequences of drone delivery? Please sort the following answers from 1 being 'most concerning' to 7 being 'least concerning' or select 'none of these'. C9. What are your greatest concerns when it comes to the possible environmental consequences of air taxis? Please sort the following answers from 1 being 'most concerning' to 7 being 'least concerning' or select 'none of these'.

figure 13 *EASA survey responses on environmental concerns*

In order to guarantee public acceptance for future development of UAM, the report recommends a series of actions for regulatory actions, including actions to ensure safety, environmental and wildlife protection. For noise, authorities should ensure that the level, frequency and duration of the related sounds is kept at acceptable levels, notably when first UAM operations start, as unfamiliar sounds are perceived as more annoying than familiar ones. It is recommended that follow-up studies are conducted to investigate positive impacts of quiet zones and times on people's acceptance, and wild-life.

Contrary to recommendations on noise to improve public acceptance, and thereby contributing to the future success of the drone sector development, the report warns that a strong focus on noise reduction could lead to high aircraft costs and costs for operations, e.g. by maximizing the number of flights or requiring higher flight altitudes. Oppositely, as the report states (p.96), "*a low focus on reducing noise footprint […] would make UAM more quickly available and could reduce the aircraft complexity. If the aircraft noise were limited to the level of a leaf blower or an old motorcycle, the aircraft costs could be lower. However, the operating cost might be higher, due to a higher flight altitude in order to achieve a set noise footprint on the ground. There could also be more noise-related complaints or law suits than for the strong focus on the noise footprint.*"

<u>EASA European Aviation Environmental Report 2022</u>
The conclusions from the EASA societal acceptance study are also included in the EASA 2022 European Aviation Environmental Report [8]. It states that EASA is developing dedicated noise certification standards that take into account the specific characteristics of UAM vehicles, as they operate in different manners and places than what was considered when existing aircraft noise standards were developed. Understanding how these vehicles are expected to fly, and what their typical missions will be, is considered fundamental to developing appropriate noise certification standards.

EASA High Level Conference on Drones 2023
In conjunction with the Amsterdam Drone Week 21-23 March 2023, the EASA held a High Level Conference on drones, discussion many different topics, developments and regulations together with authorities and industrial partners from the drone sector. One panel discussion was devoted to the societal acceptance, including also noise. The interested reader can watch this discussion on YouTube: https://youtu.be/BAc6quZ4iSc. Some highlights:

- A noise regulations expert from EASA explained (figure 14) that they are working on
  - adaptations of existing noise standards (e.g. for helicopters) to make them suitable also for eVTOL vehicles, rather than building new noise standards from scratch;
  - guidelines for a measurement method to measure drone noise consistently, which have been put up for consultation. A final version is published in June 2023, with guidelines for noise measurements of drones below 600 kg [9];
  - psychoacoustic studies performed by scientific partners (NLR, DLR); these were described in § 2.2 and in [1] and [7];
  - a noise impact assessment method, based on the earlier rotorcraft noise model NORAH[4] which started in 2017 for helicopter noise. This is now expanded to include also drone noise calculations, which can then be included in the END strategic noise mapping, i.e. CNOSSOS-EU.
- Part of the discussion focused on the importance of the use case in the societal acceptance. Health care uses (fast transport of emergency equipment or personnel, medicine delivery) are more acceptable than more individual needs. Also, the panel agreed that the introduction of drone transport may to some extent replace road transport but will surely lead also to additional transport and mobility. This was highlighted by the example case of hot coffee and food delivery by drone.

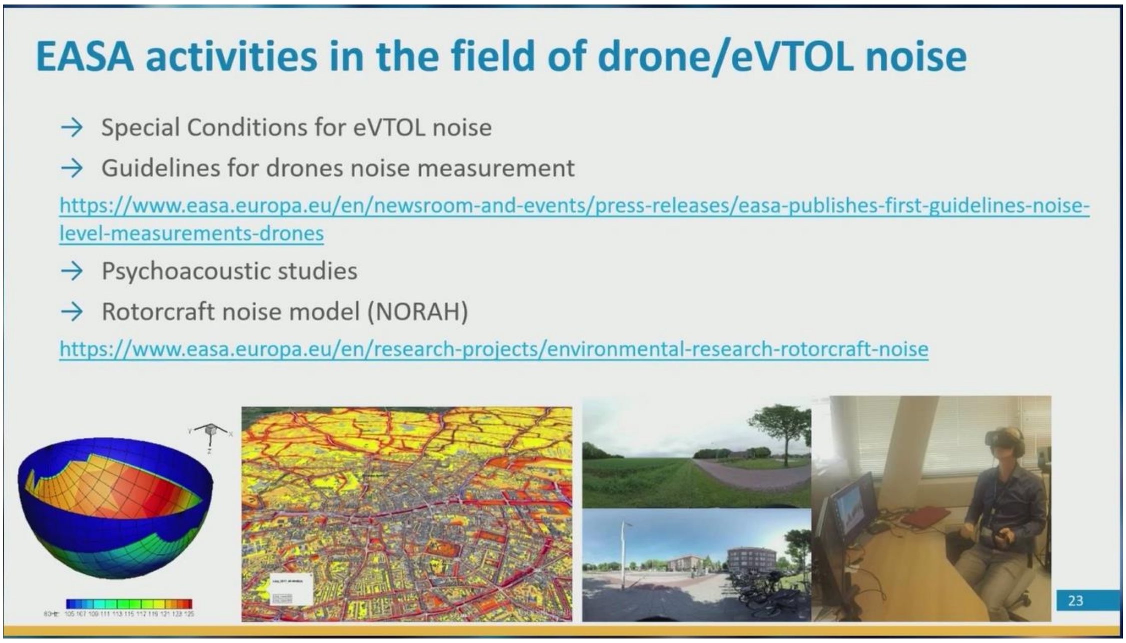


figure 14 *Slide from presentation at EASA High Level Conference on drones, March 2023, by Ivan de Lepinay, EASA Senior Expert Noise and Standards*

[4] The NORAH noise model for helicopters and drones (NOise of Rotorcraft Assessed by a Hemisphere-approach) is unrelated to the German noise annoyance research project NORAH (Noise Related Annoyance, Cognition and Health)

3.3 Regulatory framework

3.3.1 EU drone regulations

Drones, like all aircraft, fall under the aviation “Basic Regulation”, EU regulation 2018/1139, providing common rules in the field of civil aviation and establishing the EASA [12]. This regulates general safety and operational aspects, technical specifications, certification, etc. Article 9 specifies that the environmental conditions apply as defined in the international Chicago Convention.

Specifically for unmanned aircraft systems, two new regulations were launched in 2019:

- regulations for the systems and drones, including technical requirements, type approval and mandatory identification: Commission Delegated Regulation (EU) 2019/945 of 12 March 2019 on unmanned aircraft systems and on third-country operators of unmanned aircraft systems [13]

> **CHAPTER I**
>
> **General provisions**
>
> *Article 1*
>
> **Subject matter**
>
> 1. This Regulation lays down the requirements for the design and manufacture of unmanned aircraft systems (‘UAS’) intended to be operated under the rules and conditions defined in Implementing Regulation (EU) 2019/947 and of remote identification add-ons. It also defines the type of UAS whose design, production and maintenance shall be subject to certification.
>
> 2. It also establishes rules on making UAS intended for use in the ‘open’ category and remote identification add-ons available on the market and on their free movement in the Union.
>
> 3. This Regulation also lays down rules for third-country UAS operators, when they conduct a UAS operation pursuant to Implementing Regulation (EU) 2019/947 within the single European sky airspace.

- regulations for the operators and operations of such systems: Commission Implementing Regulation (EU) 2019/947 of 24 May 2019 on the rules and procedures for the operation of unmanned aircraft [14]

> *Article 1*
>
> **Subject matter**
>
> This Regulation lays down detailed provisions for the operation of unmanned aircraft systems as well as for personnel, including remote pilots and organisations involved in those operations.

Commission Implementing Regulation (EU) 2021/664 of 22 April 2021 [16] specifies the regulatory framework for the implementation of U-spaces. The regulation states that Member States can designate U-space airspaces and may impose specific conditions for all or certain UAS operations, including requirements for UAS technical features. Any restrictions must, however, be supported by an airspace risk assessment; without such support, the U-space cannot be restricted.

3.3.2 Categorisation

UAS are categorised in terms of their operations (regulation 2019/947) as well as in terms of their technical specifications (regulation 2019/945) as well as in ISO 21895 “Categorization and classification of civil unmanned aircraft systems”. With respect to technical specifications, drones must as of January 1st 2024 be marked with a class label C1 to C6 (see figure 15) where each class has specifications such as the maximum take-off mass (600 g to 25 kg) and maximum speed.

In terms of operations, drones can fall under three categories, see figure 16:

- the ‘open’ category, in which the drone does not require any authorisation and the pilot does not need to have a license. Within the open category there are subclasses A1 to A3, depending on the drone class (max. C4) as well the area of application. Within the ‘open’ category, the pilot

must always have a visual line of sight (VLOS) on the drone: he, or an observer standing next to him, must at any time be able to see the drone with his own eyes (no camera or binoculars);
- the 'specific' category, for larger drones > 25 kg and/or application beyond the visual line of sight. In this category, the operation must be authorised and registered. C5 and C6 class drones are designed for flying in the specific (or certified) category with additional safety features for flying closer to people, such as parachutes, and/or for flying without VLOS;
- the 'certified' category, for even larger drones and operation in urban areas. This applies to drone delivery services and air taxis, for instance. In this category, the drone itself must be certified and type approved, and the pilot must be licensed and trained.

The regulation seems to assume that drones are operated by a remote pilot, which may or may not have visual sight on the drone. 'Autonomous operation', without any remote pilot, is defined but only mentioned briefly, stating that the same requirements as for piloted operations apply. It is not mentioned if a single remote pilot is allowed to operate multiple drones at the same time.

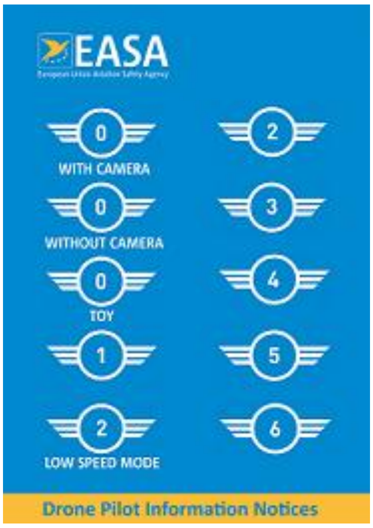


figure 15 *Drone class labels*

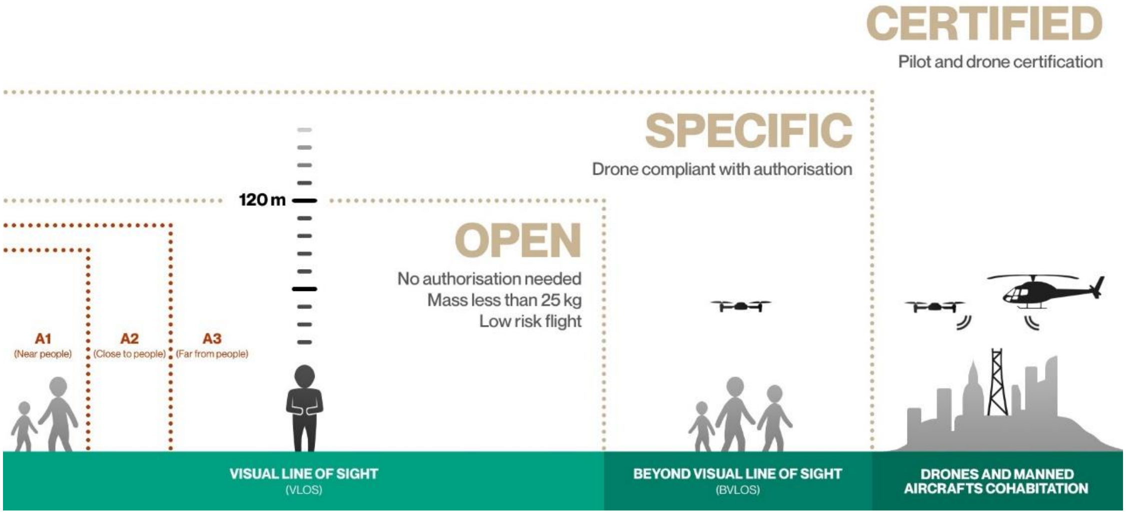


figure 16 *Drone operation categories: 'open' , 'specific' and 'certified', with subclasses for the 'open' category (from https://www.parrot.com/en/drone-regulations/eu)*

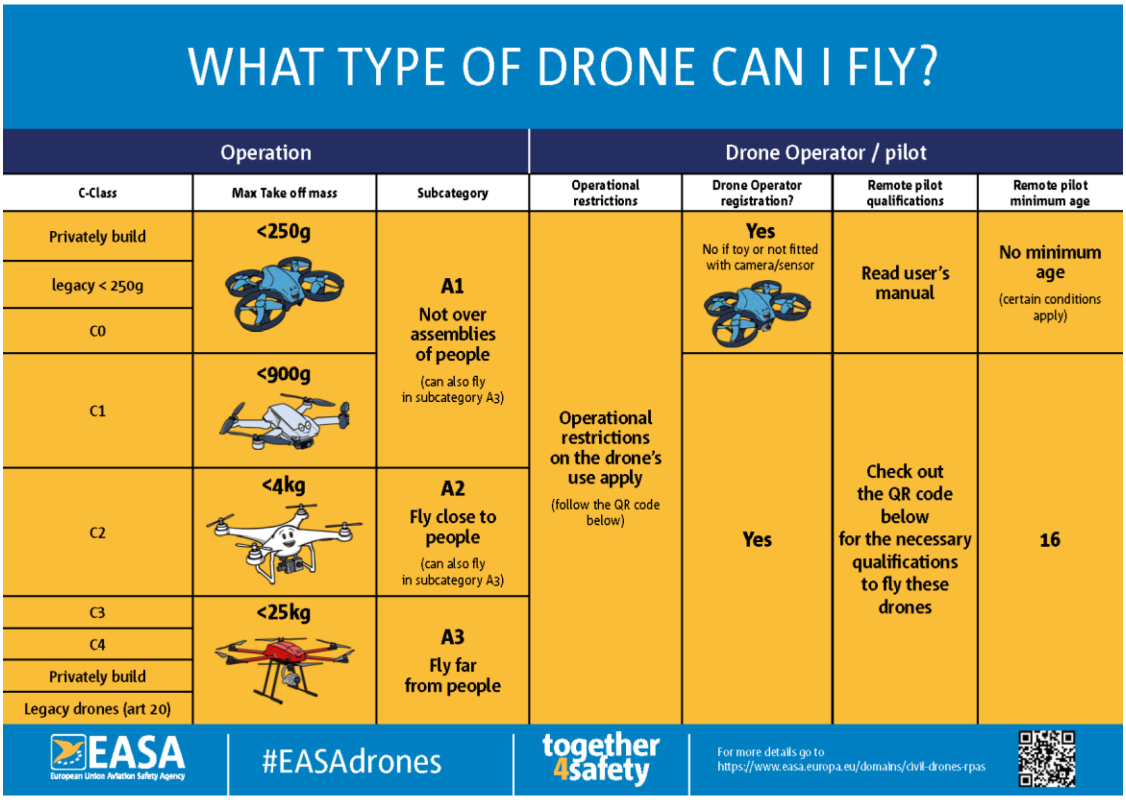


figure 17 Further details of the subcategories A1, A2 and A3 within the 'open' category

3.3.3 Noise regulations

With regards to noise, these regulations contain the following:

- Regulation 2019/945 defines how sound power levels should be measured and how they should be indicated on the drone. For this, the regulation follows the ISO3744:2010, which is the general measurement method to measure stationary noise sources in free field over a reflective plane. This method is also applied for machinery, industrial noise sources and other applications, including those within the scope of the Outdoor Noise Directive. It may be expected that newer, specific measurement methods will be made applicable in a future revision of the 2019/945 regulation.
- Regulation 2019/945 also defines maximum sound power levels at least for drone classes C1 and C2. Maximum limits range from 81 to 97 dB(A), depending on the drone mass (max. 4 kg), see figure 19.
- Regulation 2019/947 specifies noise requirements for UAS operations, but in qualitative terms:
  - Operators shall establish guidelines for its remote pilots to plan UAS operations in a manner that minimises nuisances, including noise and other emissions related nuisances, to people and animals.
  - Unmanned aircraft must be used which is designed to minimise noise and other emissions, taking into account the type of the intended operations and geographical areas where the aircraft noise and other emissions are of concern.

figure 18 *Mandatory noise label indicating the maximum guaranteed A-weighted sound power level (L_{WA}) [13]*

UA class	MTOM m in gram	Maximum sound power level L_{WA} in dB		
		as from entry into force	as from 2 years after entry into force	as from 4 years after entry into force
C1 and C2	$m < 900$	85	83	81
C2	$900 \leq m < 4\,000$	$85 + 18{,}5 \lg \frac{m}{900}$	$83 + 18{,}5 \lg \frac{m}{900}$	$81 + 18{,}5 \lg \frac{m}{900}$

figure 19 *Maximum sound power levels for class C1 and C2 drones, depending on the drone mass m [13]*

EASA has recently published two consultation papers for eVTOL aircraft with non-tilting [10] and tilting rotors [11] containing Environmental Protection Technical Specifications for noise. Here, it is proposed to introduce the use of the Effective Perceived Noise Level (EPNL) for regulatory limits for UA. The EPNL is also used for conventional aircraft noise limits, such as in the ICAO noise standards. In short, it is a frequency-weighted sound exposure level, but with additional penalty corrections for tonal components. The EPNL uses the EPNdB unit. Based on the EPNL, EASA proposes maximum levels for take-off, flyover and approach procedures as a function of the UA maximum take-off mass (MTOM).

3.3.4 Environmental Noise Directive and Zero Pollution Action Plan

The END (Directive 2002/49/EU) does not mention unmanned aircraft as a noise source specifically, but it could be considered as part of ‘aircraft’ in general. The Zero Pollution Action Plan [15] sets a 30% reduction ambition for people chronically disturbed by transport noise without further defining the scope of ‘transport’. The EU Drone Strategy 2.0 [17] does mention that it is linked to the ZPAP with a specific reference to noise. A conversation with DG ENV in September 2023 confirmed also that drones *are* considered to fall under the ZPAP definition of ‘transport noise’. In a recent meeting of the EuroCities Working Group on Noise, DG ENV has stated that EU agglomerations are actually expected to include drone noise in their five-year Noise Action Plans; Round 4 (2024-2029) NAPs are officially due in July 2024. There is, however, no guidance on what should be included in the NAP or how.

Currently, there is not yet a calculation method to quantify the noise impact of drones, by means of the strategic noise maps or otherwise. The EASA is developing the NORAH model for this purpose, to include noise from rotorcraft (helicopters and drones) in noise assessment methods, including CNOSSOS-EU. In 2024, the NORAH model was further improved in terms of the noise emission and propagation, and provided with noise emission data for several helicopter types [39]. Figure 20 shows an example of how noise emission data is provided: noise levels are defined on a hemisphere surface; such hemispheres are stored in a vehicle database which is then input to further noise propagation calculations to calculate the noise levels at further distance on the ground. In a May 2024 EASA webinar[5] the results were presented. EASA indicated that in Q4 2024, additional noise hemispheres for drones and/or eVTOLs will be published. In 2025+, the EASA will engage with the European Commission to integrate the NORAH model into the Environmental Noise Directive.

figure 20 *Illustration of the hemisphere approach: the sound emission by rotorcraft is defined as noise levels projected on a half sphere, as input to a noise propagation model for calculation of noise emissions on the ground (source: NLR)*

3.4 Other requirements

There are many requirements for drones and drone operations regarding safety, in regulations 2019/945 as well as 2019/947 and also in the general aviation regulation 2018/1139. For example, the drones themselves must be airworthy and well-maintained. They must be kept at a certain distance from people, depending on the drone technical and operational categories. The details of safety regulations will not be discussed further here.

For drones equipped with a camera or another sensor capable of recording personal data (e.g. a microphone), privacy may be of concern. And many drones, especially those in the ‘specific’ and ‘certified’ categories flying beyond the VLOS will be equipped with a camera as this is needed for a remote pilot or for the autonomous drone itself for navigation and safety. With regards to privacy, regulation 2019/947 refers to the General Data Protection Regulation (GDPR). This sets the same requirements as for other cameras and privacy sensitive equipment, in terms of protection, storage, accessibility and processing of such camera images and other personal data.

[5] https://www.easa.europa.eu/en/newsroom-and-events/events/webinar-upgrade-noise-rotorcraft-model-norah-final-dissemination-event

Additionally, the 2019/947 requires that operators of unmanned aircraft equipped with such sensors must be registered, unless it is considered a toy (according to Directive 2009/49/EC).

In general, regulation 2019/947 states that it *should be without prejudice to the possibility for Member States to lay down national rules to make subject to certain conditions the operations of unmanned aircraft for reasons falling outside the scope of this Regulation, including environmental protection, public security or protection of privacy and personal data in accordance with the Union law.* So, besides the general requirements that limit operations in the 'open', 'specific' and 'certified' categories, Member States can define their own areas ('UAS geographical zones') in which drones are or are not allowed to operate. Also, it is a requirement from the U-space definition that drones are 'geo-aware', which means the drone itself, based on digital data provided by the Member States, has real-time data on where it is, and if it is in an area that it is allowed to be in. If not, the drone should have a mechanism to alert the remote pilot.

4 Future expectations

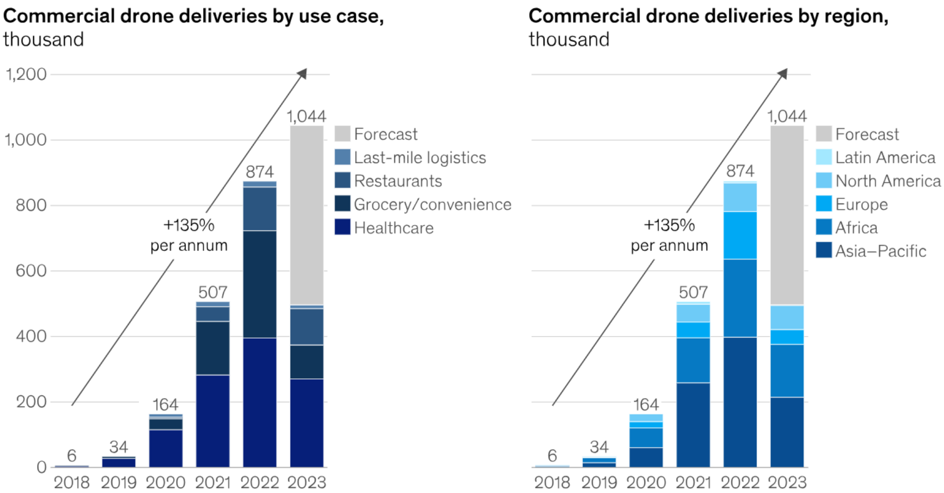
4.1 Current and expected status of UAM

According to internet sources, the total number of drone shipments worldwide is expected to have reached 1 million in 2023[6]; definite number for 2023 are not yet available at the time of writing. The number of commercial drone deliveries has increased quickly over the last few years, see figure 21. These numbers are currently negligible with respect to the billions of yearly worldwide shipments. A steep increase of drone shipments is expected in the next years, however. The total economic value of the drone market is expected to raise from close to 30 billion USD[7,8] to 55 – 77 billion USD in 2030. This is a quickly developing market, with large economic opportunities for drone producers and service providers. It is difficult to predict how quickly and to what extent users and consumers will embrace this new form of transport. Also, the development will depend on what will be allowed by the EU, local governments and airspace authorities, with regulations being currently developed.

We have not yet found commercial applications of passenger transport by drone, i.e. air taxis, either with or without a pilot on-board, other than test flights. Air taxis require larger drones, more similar to small helicopters, which could pose a noise issue already at lower volumes especially around the landing/take-off sites (vertiports). First pilot projects, followed perhaps by larger scale applications, are expected in 2025, see e.g. § 5.5.

There seems to be little doubt that significant growth is expected, and that all Europeans will observe some drones in the skies before 2030. To what extent this will evolve into a volume that may pose a noise and health problem is difficult to predict, but it seems fair to raise concerns on this potential future issue.

Commercial drone deliveries are projected to exceed 1 million in 2023.



Note: Number of deliveries represents number of parcels delivered, not total number of items within the parcels.
Source: McKinsey Drone Delivery Tracker and Forecast

figure 21 Number of yearly parcel deliveries by drone worldwide since 2018, with forecast for 2023 (source: McKinsey[6])

[6] https://www.mckinsey.com/industries/aerospace-and-defense/our-insights/future-air-mobility-blog/commercial-drone-deliveries-are-demonstrating-continued-momentum-in-2023

[7] https://www.strategicmarketresearch.com/blogs/drone-industry-future

[8] https://droneii.com/drone-market-analysis-2022-2030

4.2 Relevance of UAM to society

4.2.1 Use cases

Current use of drones includes application areas such as:

- agriculture: monitoring of crop and livestock for large farming areas, as well as fertilization and irrigation;
- construction, infrastructure and mining, mainly for inspecting and monitoring large and/or remote sites, e.g. for maintenance or inspection of problems. Drones are used for autonomous inspection[9] and delivery of tools and parts[10] to offshore wind farms, for example. For this, drones may be equipped with specialised equipment such as thermal cameras or Lidar sensors;
- mapping and surveying: identifying and measuring the layout of ground areas from the sky, as well as surveying nature areas and wildlife. Drones are also applied for purposes of safety, police searches and crowd management, although stricter regulations apply in case of overflying people (see § 3.3.2);
- medical deliveries, such as organ transport or other time-critical medical deliveries, or delivery of medical supplies, defibrillators and medication to more remote areas;
- parcel delivery and e-commerce: package transport, particularly if it is time-critical, such as hot food and beverages;
- photo- and videography, either on a professional level or by amateur photography and filming;
- hobby and toys: amateur hobbyists use (typically smaller, category A1) drones for fun, including drone racing events, also indoors.

In 2022, the top-3 industries[11] applying drone technology were energy, construction and agriculture, and drones were mainly used for mapping & surveying, inspection and photo- and videography. An increase of drone use is expected for all application areas, but specifically for deliveries. Several specific use cases of existing drone delivery services around Europe are described in Chapter 6 below.

Military drone use is not covered within this report. However, as with conventional military aircraft, increased annoyance and sleep disturbance may be expected around training locations and/or during military exercises. Also, locations used for civilian drone training, certification and/or testing may also lead to health impacts and complaints from local citizens.

4.2.2 Pros and cons

Short time to delivery

Drone delivery is relatively quick, as a flight route is typically much more direct and shorter than ground-borne transport. High-end delivery drones can fly up to 70 or 100 km/h, which is typically faster than the average speed of a car, van, moped or bicycle on the same route. Within a range of a few km, drone delivery is just a few minutes, which allows for very time-critical deliveries which would not be possible by any other means of transport. However, drones will not be able to deliver to the front door or back yard in all cases. In denser urban areas, for apartment buildings, etc., drones may only be able to deliver to specific landing sites and local pick-up centres, which requires additional time for the pick-up, whereas car, moped or bicycle delivery may come directly or closer to the recipient’s home.

[9] https://www.tno.nl/en/newsroom/2023/09/windturbine-inspections-drones/

[10] https://orsted.com/en/insights/expert-take/drones-to-save-time-and-money-in-offshore-wind

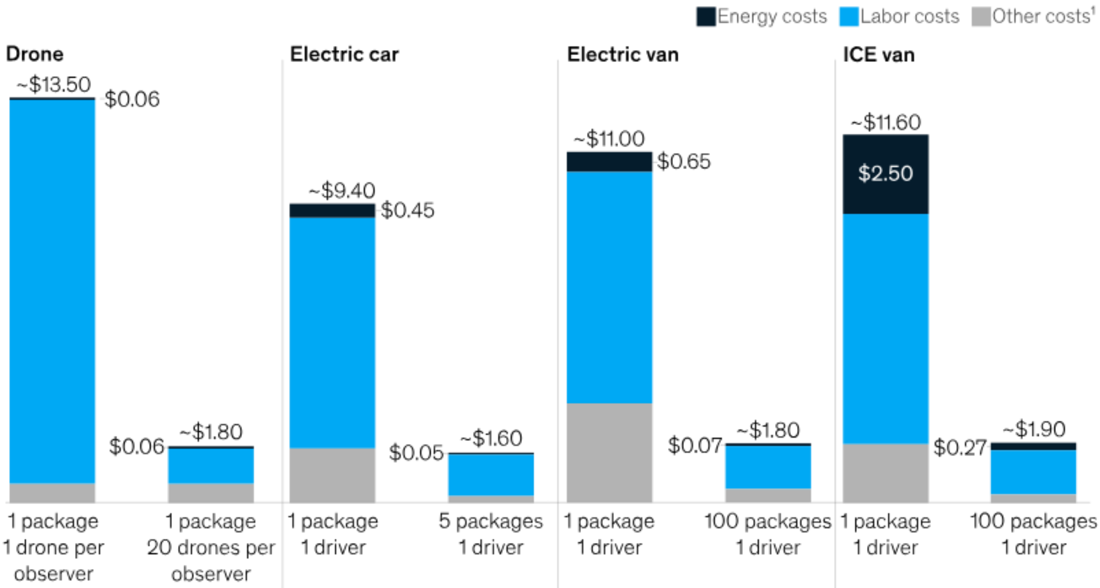
[11] from https://droneii.com/top-drone-applications [accessed 2023-12-06]

Costs

Drone delivery can potentially be cost competitive with transport by car or van, as illustrated by figure 22. For transport, personnel costs are the biggest cost factor. Relevant for the cost competitiveness of drones is the number of drones per operator. If each drone is operated continuously by one pilot, the labour costs will be too high to compete with car delivery, as a car (or van) can carry many packages to drive (part of) the same route at the same time. Further developments of technology (i.e. autonomous flight) and regulations may allow operators to operate / monitor multiple drones at the same time, which dramatically decreases personnel costs.
In case of single-package deliveries or deliveries of small quantities, such as food, drones may already be cheaper and more environmental-friendly than road transport.

Sustainability

Drones are basically all electric. Although gas-powered drones do exist, and their action radius would be larger than for electric drones, all drone manufacturers and service providers seem to utilize only electric drones, and this is part of their strong points and future business case. (Electric) drone transport comes with significantly lower CO_2 emissions than road transport with combustion engine vehicles (see the bottom table in figure 22). For single-packages, drone delivery also is advantageous over electric car/van delivery, but if compared with multiple packages per car, drones do require more energy per package. Also, the sustainability advantage of electric drones would require that the electricity stems from clean and renewable energy sources.



Emissions,[2] kg CO_2e							
1.07	1.07	1.40	0.14	2.08	0.20	6.4	0.64

[1]Other costs include asset, maintenance, and insurance costs.
[2]Scope 2 and Scope 3.

figure 22 *Example breakdown: unit delivery and emissions for a five-mile delivery of a 216-cubic inch package (six inches per side); source: McKinsey*[12]

[12] https://www.mckinsey.com/industries/aerospace-and-defense/our-insights/future-air-mobility-blog/drones-take-to-the-sky-potentially-disrupting-last-mile-delivery

Safety and privacy

Concerns about safety and privacy are among the most important societal acceptance factors for drone delivery, as discussed in § 3.2. People worry about air collisions of drones with other aircraft around airports, with each other, or with birds and potentially people. Also, the delivery of drone packages, being tethered or parachuted from a certain altitude, could be unsafe.
Although concerns about safety are understandable, professional drones and operations are not inherently unsafe or less safe than other transport modes. Safety does require adequate regulations and air traffic control, and such are currently being developed, see Chapter 3.
Privacy is a valid concern as many drones will rely on on-board cameras for (remote) navigation. The idea of being watched by a remote pilot, or of images / videos being taken, stored and published, will worry people and lead to annoyance, complaints and anger.

Noise

Clearly, noise is a potential future problem for drones, given their particular characteristics (see Chapter 2) and the associated higher annoyance levels. Drones may come relatively close to people, although some drone delivery companies advertise drones as a quiet means of transport, compared to road transport. These claims are under the condition that they will not have to fly at low altitudes because packages can be lowered from the sky.

Other

Other pros and cons include:

- benefits for entertainment, TV / media production and other photo-/videography applications that are not possible without drones;
- concerns about visual pollution;
- concerns about concentration of drones around sport and other events, and around local landmarks.

4.2.3 Discussion

Several of the anticipated or claimed advantages of drones rely on a comparison of drones with other modes of transport. For example, some expect or claim that drone transport will relieve road transport, leading to less road transport and less traffic jams. However, as brought forward by others, see e.g. the literature review in [24], it may be expected that short delivery times and lower delivery costs will lead to increased demands, more deliveries and an overall increased mobility. Drones will more likely add to existing transport than replace it. In that respect, claims of positive effects on sustainability, noise and safety should be considered with some scepticism.

5 Case studies and example applications

5.1 Manna

Manna (https://www.manna.aero) is an Irish company that provides drone delivery services for consumers. Manna delivers mainly food and beverages from different stores in the local shipping centre. Other deliveries include books, pharmacy products and printer ink. Due to the fast response time (< 3 minutes between take-off and delivery), they are also able to deliver hot coffee and meals or frozen products, which is their main selling point. Manna is has been operational in the small town of Balbriggan, below Dublin. As announced in the EASA panel discussion (see § 3.2) they are now available in Blanchardstown near Dublin as well as in Pecan Square, Texas USA.

Orders are placed with a smartphone app (figure 23). Packages are delivered in the backyard by lowering from the drone with a biodegradable thread (figure 24). It is not fully clear from the website if the drones are operated by remote pilots, or if they fly autonomously with remote pilots only taking over in case of difficulties or emergency. The company claims are that their drone delivery is green, as it runs on electric power, that it is safer than road vehicles and that it is also quieter than road traffic, as the drone will not fly lower than 60 m altitude.

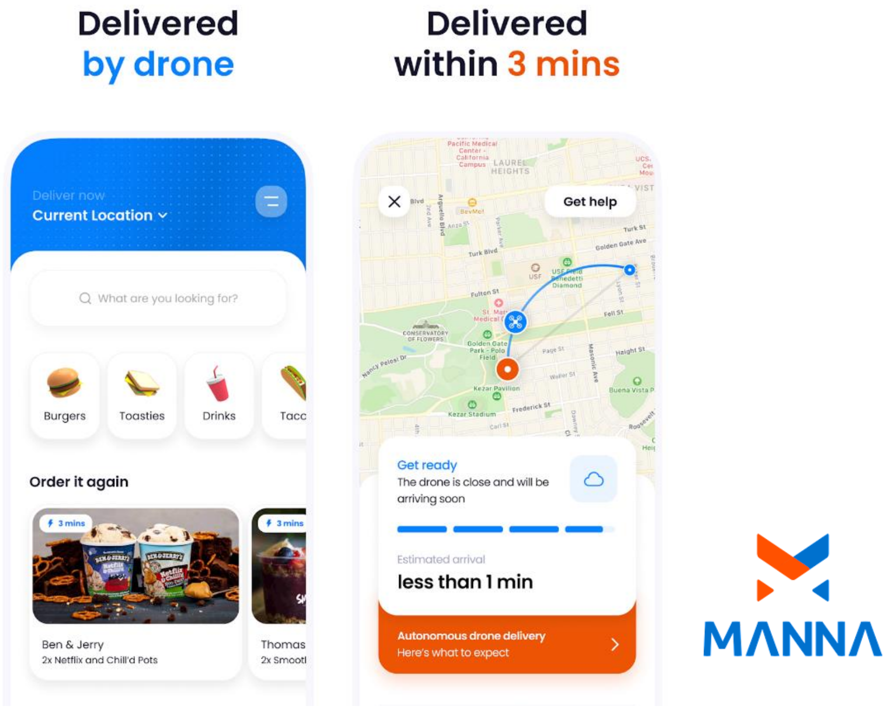


figure 23 *Screenshots from Manna Drone Delivery app (source: Google Play store[13])*

[13] https://play.google.com/store/apps/details?id=com.manna.mannaorderapp&hl=en_IE&gl=US

figure 24 Screenshot from Manna video (https://youtu.be/oTJKo15rqtc) showing package dropdown.

5.2 Kyte by Aviant

In Norway, logistics company Aviant (https://www.aviant.no/) is operating a commercial drone delivery service, Kyte (https://kyte.delivery/). It has been active in Trondheim since 2023, after delivering medical supplies and transporting Covid-19 tests during the pandemic, and is now operational in a few other locations in Norway and Sweden. Similar to Manna, people can order groceries and food using a smartphone app, to be delivered to their home and dropped from 60 m height into the garden using a tether. Aviant claims that the flight range for their drones of typically 30 km (one-way) is considerably higher than for other similar service providers. In Norway, this is particularly attractive for people in cottages outside the urban area, where car delivery is less efficient. Around Sjusjøen, a popular cottage area for people living in Oslo, there have been complaints from people annoyed by the noise and worrying about safety [3].

5.3 Wing project by Google

The innovation laboratory Google X, part of Google's parent company Alphabet, has launched project Google Wing[14] that performs delivery by drone. Wing has now evolved from Google X into a separate Alphabet company.

According to their website, Wing's drones operate autonomously. The development of drone services by Google started in 2012. Wing currently operates in Texas (US) and has operated in Helsinki and in Canberra (Australia); it says to have delivered >300.000 commercial packages. The company claims that drone delivery is fast, safe and green, or at least 'more ecologically friendly than what's possible today on the ground'[15]. Noise is not mentioned.

In the case of Canberra, the pilot project in the Bonython suburb led to significant opposition from local inhabitants [4], threatening to shoot the drones out of the sky, while other inhabitants favoured the quick delivery service which was not available with road transport modes before.

[14] https://wing.com

[15] https://x.company/projects/wing/

5.4 Wingcopter GmbH

Wingcopter[16] is a German manufacturer and service provider for delivery drones. Their mission is more oriented towards community and humanitarian applications, such as health care, delivery of medical goods to more remote areas, and inspections of vulcanoes, wildlife and infrastructure (see https://wingcopter.com/project/success-stories). Their website does mention also commercial applications, parcels and E-commerce. Another example project is delivery of industrial goods for Merck in Germany.

Technically, Wingcopter provide larger drones that are more suitable for longer distances (i.e. up to 75 km) and heavier loads, also for rainy and windy situations, and claim to need a lesser degree of people monitoring the autonomous drone flights. Noise is mentioned in some of the example projects, for instance the claim that the low noise emission of their drones present no disturbing effect on the wildlife animals being surveyed.

5.5 VoloCopter air taxi

The German-based VoloCopter[17] is one company that produces eVTOL air taxis and aims to deliver passenger transport services, as well as cargo transport. For air taxis, they have developed the VoloCity model that can accommodate two passengers for shorter distances (see figure 25) and the larger VoloRegion model that can hold four passengers for intercity traffic.
Together with the Italian vertiport network operating company UrbanV[18], a commercial air taxi service is planned to be running between Rome centre and Rome Fiumicino Airport by the end of 2024, aiming to be ready for the 2025 Christian Jubilee and with further expansion to 8-10 vertiports before 2030. For the 2026 Winter Olympics in Milan, vertiports will also be constructed to enable air taxis. Tests with Volocopter air taxis have also been done at Tampa International Airport in Florida (US), which was promoted as the starting point of the entry of such services in the U.S. [32]. No clear timeline for further development is given.

figure 25 VoloCity air taxi by VoloCopter GmbH

5.6 Ehang

Chinese eVTOL manufacturer Ehang (https://www.ehang.com/) produces several air taxi models, with the EH216 as their current most successful model (see figure 26). The EH216-S multicopter aircraft hosts 2 passengers, with a range of 35 km and 100 km/h cruise speed. Ehang has received an airworthiness type approval certificate for this model, certified by the Chinese civil aviation

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[16] https://wingcopter.com/

[17] https://www.volocopter.com/en

[18] https://www.urbanv.com/en/

authority. Ehang has planned commercial air taxi service to be operational by the end of 2024, although no further details could be found.

figure 26 *Ehang EH216 multicopter air taxi*

5.7 Other example providers

Among other examples of drone manufacturers and drone delivery services are:

- Zipline[19]: an American company operating since 2016 with >1,000,000 deliveries made since. Their services range from health care, medical supplies, agriculture to food and retail products. Zipline states that their drones are autonomous, capable of traveling without any pilot oversight under normal environmental conditions, if allowed. In the US, the Federal Aviation Administration has authorised BVLOS flights, where the drone flies autonomously while being monitored by a remote pilot;
- Amazon Prime Air[20]: announcements of services starting in California and Texas. Amazon Prima Air has also obtained FAA approval for BVLOS drone flights;
- Matternet[21]: provides drone package transport in urban areas, currently between hospitals, using local ‘docking stations’ (figure 27) rather than dropping or tethering packages to individual homes;

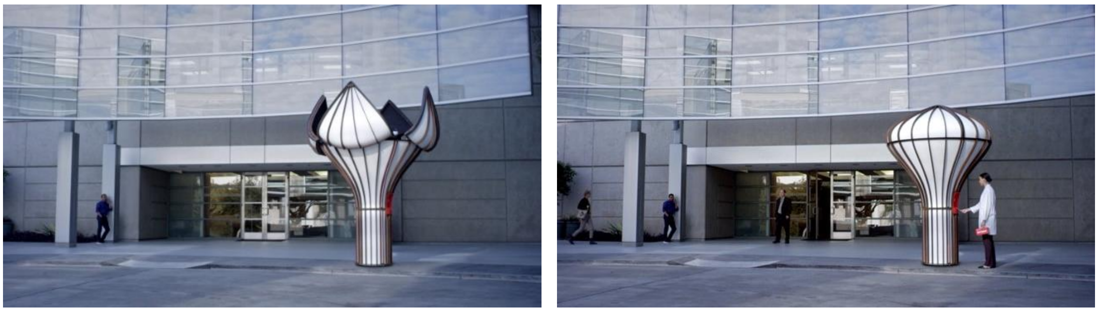

figure 27 *Matternet’s drone landing station provides a package pickup point as well as drone charging (source: Matternet)*

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19 https://www.flyzipline.com/

20 https://www.aboutamazon.com/news/transportation/amazon-prime-air-prepares-for-drone-deliveries

21 https://mttr.net/

- Nepalese drone services provider Airlift technology together with drone manufacturer DJI successfully delivered supplies and brought back waste from the Mount Everest base camp to Camp 1 at 6.000 m above sea level, under extreme conditions[22]. A regular drone service is expected to be operational in 2025, to replace some of the work normally done by Sherpas.
- In the U.S., both Joby Aviation (https://www.jobyaviation.com/) and Archer Aviation (https://archer.com/) are producing air taxis for passenger transport services, for instance between New York JFK airport and heliports down town. Both companies are developed tilt-rotor eVTOL models for this. With respect to noise, Joby states that their aircraft *would almost certainly be undetectable against the everyday noise background of an urban environment*. Archer on their website claim that their Midnight eVTOL model is *up to 100x quieter than a helicopter when flying at cruising altitudes, making them virtually inaudible from the streets below*. The statement is accompanied by the image in figure 28, which seems to compare the noise footprint of their Midnight eVTOL model to that of a Leonardo (formerly Agusta) A109C, a helicopter model that exists since the 1970's.

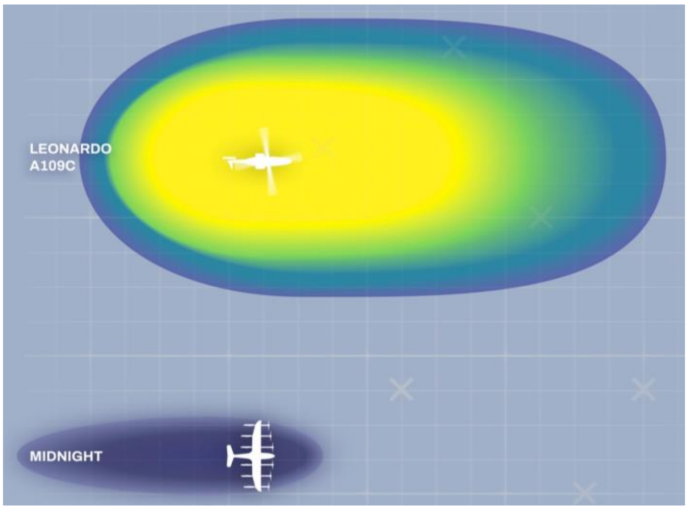

figure 28 *Comparison of Leonardo A109C helicopter vs. Archer Aviation Midnight eVTOL (source: https://archer.com/aircraft)*

[22] https://www.dji.com/nl/media-center/announcements/dji-completes-world-first-drone-delivery-tests-on-mount-everest-en

6 Recent and ongoing research

As the development of drone technology and its applications is rapidly developing over the last years, so is the research surrounding this development, including research on drone noise. Illustratively, the reference list at the end of this report contains publications almost exclusively from the last ten years, with the majority not older than five years.

With regards to drone noise, we are aware of ongoing research in the field of low-noise drone design, harmonised measurement methods, calculation methods, perception and annoyance studies and route optimisation. Some of the European institutions involved in this research are listed below. This list is likely to be incomplete; there will be other public organisations and private companies doing similar research that we are currently unaware of.

- The European Union Aviation Safety Agency (EASA) have been studying societal acceptance [6] and perception [7]. They have also published guidelines for noise measurements on unmanned aircraft below 600 kg [9] and are working on improving the NORAH2 calculation model for UA noise, enabling inclusion of drones in noise mapping [39]. See https://www.easa.europa.eu/en/domains/civil-drones.
- The University of Salford in Manchester (UK) is performing and publishing extensive research on drone noise measurements and perception studies, see also some of the references used for this report, e.g. [26][33][34].
- The Netherlands Aerospace Centre (NLR) is studying many aspects of drones, including noise and noise perception. The NLR started a Drone Centre (https://www.nlr.nl/dronecentre/) in 2013 to facilitate research, testing, type approval, flight training and pilot certification. They also have an outdoor test centre (https://www.nlr.nl/dronecentre/testcentrum/) as well as indoor laboratory and auralisation environments.
- Together with NLR, the Technical University Eindhoven is researching the noise perception of UA in urban areas, including also an efficient means of modelling the propagation of such sounds in urban environments [41].
- The Swiss federal research institute EMPA is working on drone noise measurements, perception and on auralisation, i.e. to accurately and representatively reproduce such sounds in a 3D laboratory environment or in other VR applications, which enables perception research.
- Other relevant research parties include the German Aerospace Center (DLR), the French Aerospace Lab (ONERA) and the University of Delft (NL), among others.

We recommend the review by Salford University [26] which summarises a large number of recently published research studies and other literature concerning different aspects of drone acoustics and perception.

On EU level there are several recent or ongoing research projects, including:

- the Horizon Europe project RefMap (https://www.refmap.eu), which focuses on prediction and optimization of flight traffic trajectories and patterns in order to reduce the environmental and noise impact on communities and wildlife. Although regular aviation is also within the project scope, there is specific focus on drones;
- within the SESAR Joint Undertaking (JU) public-private partnership, the ImAFUSA project (https://www.imafusa-sesar.eu/), which focuses on different aspects influencing the societal acceptance of drones: environmental impact (including noise), safety and socio-economic aspects;
- also within SESAR-JU, the MUSE project (https://musesesarproject.eu/) aims at development of key performance indicators, methods and tools to assess the impact of UAM operations on liveability and quality of life in cities, including noise. A 2024 conference paper by ONERA [25] demonstrates the development of tools to generate drone flight trajectories, including VTOL in-

flight performance parameters, which are then fed into noise emission and propagation models, which enables calculations of the noise impact for a fleet of multiple drones.

We have not made an extensive overview of research outside of Europe. It should be mentioned that the NASA is quite active on the field of drone noise, see e.g. https://ntrs.nasa.gov/citations/20205007433. They are the leading party in the USA in the field of drone community noise, working together with the Federal Aviation Administration (FAA), drone manufacturers and international partners.

7 Conclusions and recommendations

7.1 Conclusions

Drones are an emerging new form of mobility that is expected to rise quickly. They are typically suitable for short-distance and low-weight transport of goods and people, as well as surveillance purposes. For delivery of packages and surveillance, drones are already in use, albeit in very small numbers currently. It may be expected, however, that all Europeans will start seeing and hearing drones regularly in their living area before 2030.

The development of urban air mobility using drones and air taxis is welcomed and stimulated both by governments and industry. The expectation, or at least the narrative, is that it is a fast and sustainable alternative to other land-based transport modes, and that the use of drones will lead to less road traffic. As drones make use of currently unused traveling space, they will reduce traffic congestion and/or allow an increase in mobility without increasing congestion. The replacement of road traffic by drones is also associated with environmental benefits, i.e. lower air pollution and also noise levels as drones will fly at high altitudes further away from people. Also, the economic potential of the development of a new urban air mobility sector is very promising to both industry and governments.
Some critical remarks are placed by others, who claim that drones will not reduce road transport but mainly add on to it, leading to increased energy consumption, noise and privacy issues. Overall, mobility and general consumption are expected to increase.

Acoustically, drones have a distinctive and unusual sound, depending on the model and type, that is shown to be more annoying than other transport sounds, including aircraft noise. Drones mostly use propellers that make tonal, buzzing or whining sounds that capture people's attention. In terms of psychoacoustic indicators, this means that besides their loudness, drones exhibit relatively high sharpness, tonality and roughness compared to other sources. Psychological aspects and non-acoustic factors can be assumed to play an important role: the fact that the sound is (currently) unfamiliar, added to people's worries about safety and privacy. Research from EASA shows that noise and environmental problems, including wildlife, are the top concerns of people when asked about future drone expectations, although their general attitude and expectations towards urban air mobility are positive.
People's attitudes strongly depend on the use case: societal beneficial applications, such as medical emergencies and supplies, infrastructure surveillance and deliveries to remote areas are more positively regarded than door-to-door shopping and food deliveries. This may also depend on how and where drones are expected to fly: as their main added value seems to be in last-mile and front door / backyard drop-off, commercial home deliveries are more likely to occur in residential areas.

In summary, we conclude that:

- drones are already in our skies, and there is no doubt that they will be regularly seen and heard by EU citizens within 5 – 10 years;
- combined with the acoustic characteristics of drones, there are justifiable concerns about their considerable future impact on noise and health;
- urban air mobility in general, and certainly the noise and health aspect of it, is a young and dynamic research field, where many aspects are not fully known and under investigation. This includes the acoustic perception and response to drone noise, as well as long-term health effects. It is assumable, however, that negative health impacts that are associated with noise from existing transport modes (road, rail and conventional aircraft) will also result from drones;
- there are undeniably positive aspects to drones, in terms of economic development, sustainability and benefits from societal applications (e.g. healthcare, public services);

- the drone industry, as well as the European Commission, regard this as a positive development. Noise is seen and communicated as a problem of 'acceptance', which implies that a common future presence of drones is a fact that needs to be made acceptable, rather than opposing this development;
- EU regulations for noise are under development. Current type approval regulations do provide sound power level limits for certain categories of drones, although specific measurement methods are still being developed. This is also the case for drone traffic noise modelling. Regulations for drone operations generally prescribe that operators and pilots should avoid causing annoyance or impact nature, but without quantitative or SMART guidance. In general, it is the responsibility of local authorities to decide where and when drones are allowed to operate.

7.2 Recommendations

From the findings in this report, with regards to noise from unmanned aerial vehicles, we formulate the following recommendations.

EU institutions, the Commission and the EASA

- should regard noise from drones as a serious threat to future public health and well-being, as well as to wildlife;
- should start discussing and communicating it as such, rather than a mere issue of societal acceptance;
- should consider and communicate drone noise to be included their definition of 'transport noise', as meant in the Zero Pollution Action Plan ambition to *reduce the share of people chronically disturbed by transport noise by 30%*. Guidance is needed to help agglomerations include appropriate actions in their Noise Action Plans, as most Member States and cities currently have no idea how to address this topic;
- should continue developing a noise assessment method to include drone noise in END Annex II (CNOSSOS-EU), to enable the inclusion of drone noise in the END noise maps, which are the tool used to monitor the progress for the ZPAP ambition. Also, the exposure-response functions defined in END Annex III need to be adapted or expanded as they are likely to be inadequate given the particular acoustic and non-acoustic characteristics of drones. Psychoacoustic indicators must be considered as existing common metrics to quantify the exposure, such as L_{den} / L_{night}, are less appropriate for drone noise. Additionally or alternatively, penalty factors for tonal noise or other acoustic characteristics could be considered to correct the L_{den} / L_{night} for the higher annoyance;
- should facilitate further research into effective spatial and urban planning measures, and provide guidance to local authorities, as it is local governments where the EU Drone Strategy assigns this responsibility and mandate to. Also, they should ensure that other regulations, e.g. those guarding freedom of movement, do not interfere with this mandate. Any such activities should happen fast, within two years, in line with the rapid development of the urban air mobility sector;
- should coordinate and cluster research activities currently going on at various national aerospace laboratories, universities and other research institutions, thereby enabling researchers to work together, for instance by initiating further joint research calls;
- should, especially in the upcoming years, regularly review and update drone (noise) regulations, with adequate involvement of citizens and the noise community. It may not be before there are many drones in the skies that real issues, including complaints, annoyance and health problems, will start to arise, at which point it will be much more difficult to put the lion back in its cage;
- could consider expanding the scope of the Balanced Approach Regulation (EU Regulation 598/2014) to include unmanned air mobility, as the available noise measures are similar to regular aircraft noise, i.e. source reduction, land use planning, operational procedures and operating restrictions.

The drone industry and drone service providers

- must seriously consider and limit the noise impact from their drones and drone operations on citizens and wildlife, as prescribed already in the EU Regulations (2019/945 and 2019/947) as well as the EU Drone Strategy 2.0;
- should be aware that failing to do so will lead to complaints, annoyance, mental and physical illness, which is not sustainable and will counteract the economic success of their sector;
- are strongly encouraged to focus their research and innovation efforts on making drone propellors and propulsion systems as quiet as possible. Other measures for mitigation drone noise in urban areas are very limited, and operational restrictions may be the only alternative;
- should be open to discussion and work together with the acoustic community in research cooperations aimed at noise prevention and improvement of low-noise drones and operational procedures.

Cities and other local authorities

- should familiarise themselves with the topic of drones, be aware of their potential future noise impact and start thinking and discussing about local policy;
- should be aware of their key role in the future of drone mobility, as they are in control of their local airspace. Cities should expect and prepare for decisions on where, when and how they will allow drones to operate, as any restrictions they would want to apply need to be supported by risk assessments. In the near future, they may expect requests for permissions to operate from drone service providers on one hand, and requests for prohibiting this from residents on the other hand;
- should engage with their local residents by informing and consulting them, and having them participate in choices to be made. For instance, citizens should be involved in decisions where to locate vertiports, how to route drone traffic through the city, and more generally on the trade-off between opportunities and risks regarding this new form of mobility;
- include the subject of drone noise in their END noise action plans, if not for the ongoing Round 4 action plans then for the upcoming action plans in five years. Agglomerations should also be prepared to include drone noise in their strategic noise maps, as it is expected that these will be included in the END Annex II by the next round of mapping. They should be involved in the development of the mapping methodologies, such as how to obtain input data;
- work together with other cities and local authorities, as well as with their environmental protection agencies, national authorities and other stakeholders. Given that many will be confronted by similar questions in the upcoming years, a joint approach will be more effective and efficient. EuroCities, POLIS and other city networks could play a role in facilitating such cooperation.

Acoustics and noise & health experts

- must continue current research efforts in the field of drone acoustics, noise modelling, noise perception and health impacts, and take up new research efforts in these areas. In particular, research into measurement methods to enable unambiguous regulations as well as the added value of additional metrics and the influence of non-acoustic factors should be continued. Given the distinct characteristic sound emitted by drones, psychoacoustic indicators including spectral and tonal features as well as time fluctuations will be particularly relevant;
- must be open for discussion and cooperation with EU and other stakeholders as well as the urban air mobility industry and take an active position, to ensure that all stakeholders are well informed and aware of the potential impact of drones on environmental noise and citizen’s health;
- should promote drone noise as an emerging potential health problem by psychoacoustic characteristics, and raise awareness of this among the public, their peers and the authorities.

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