Noise exposure from drone traffic

-Scenarios and perspectives for analysis and control

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Summary

There is strong pressure to develop a drone industry. Investments are made by the industrial partners but there is also drone strategies at EU and national policy level. One reason is to address challenges for urbanization and climate impact from transportation. In addition, the EU: s transport commissioner says "We believe that if our (drone)strategy is implemented properly, the drone market could be worth 14.5 billion euros ($15 billion) by 2030. It could also create 145,000 new jobs in the European Union". The key word here is PROPERLY. Managing noise from drone transport systems will be crucial for societal acceptance. If noise and disturbances are not adequately considered, there is a risk that the realization of these innovations may be delayed or hindered by constraints in planning and approval processes or result in restrictions on established drone services.

Through the development of a simulation platform SAFTu, and a framework for implementation aspects of drones in an urban setting the APIS project provides tools and methods for addressing drone noise and annoyance, properly. The project is carried out with a broad approach and the project groups have engaged with stakeholders in discussions and interviews with the Swedish Transport Administration, Sweden's' municipalities and regions, the Environmental Protection Agency, LFV, manufacturers, and interest organizations.

One key delivery of the project is the SAFTu noise prediction software. This tool enables the calculation of the ground sound pressure levels from UAV (Urban Aerial Vehicle) flights. Noise level contours based on different noise metrics can be determined and displayed on a map. The number of inhabitants exposed to noise levels within a sound level band can be presented in histogram form. A framework for determining UAV sound source models and implementing such models into SAFTu is established. Vehicle noise source models based on field test noise data from two delivery UAVs have been implemented in the software.

Two scenarios for use-cases in the Stockholm region and in Jämtland county are addressed, representing potential implementations of UAM (Urban Air Mobility) for transport of goods. SAFTu is used to assess noise levels and in one case the number of inhabitants exposed.

Two scenarios for UAM implementation at different scales are analysed with respect to trade-offs between goal achievements and conditions for innovation within a city, including its citizens. Both scenarios have advantages and disadvantages. This complex interplay is described in the conceptual framework for the implementation of UAM (WP1).

Before UAM introduction it is recommended that noise mapping simulations are used to evaluate noise effects related to choice of UAV type and operational settings and to optimize flight routes. Simulated results can also be used to communicate the effect of drone services and noise control measures to the affected citizens and for training and awareness purposes fostering competence and acceptance with actors and citizens.

It should be noted that the computation of noise from UAV flights on the ground could not be handled by current aircraft noise mapping standards (like the ECAC Doc.29 method). So, to establish possible future UAM noise footprint new tools like SAFTu are needed.

The APIS project aims to raise awareness, develop knowledge, and provide methods that will support stakeholders in the development and implementation of drones in urban environments. Given the project findings and previous experiences, it is also observed that consequent noise regulations and guidelines for drone operations are needed. To support the introduction of UAM in Sweden more research in this area is needed both regarding accurate noise modelling and analysis methodology and methods to minimize acoustic annoyance.

Sammanfattning

Det pågår en omfattande utveckling av drönare i hela världen. En ny industri kring olika drönarkoncept håller på att växa fram. Det investeras i utveckling av farkoster, tillhörande teknik och infrastruktur. Drönarutveckling drivs aktivt på EU nivå och nationell nivå med en förhoppning om att drönartjänster ska bidra till ökad mobilitet och minskat klimatavtryck från transporter. EU:s transportkommissionär säger dessutom: "We believe that if our (drone)strategy is implemented **properly**, the drone market could be worth 14.5 billion euros ($15 billion) by 2030. It could also create 145,000 new jobs in the European Union”. Nyckelordet här är properly, eller ordentligt. För att realisera UAM-konceptet (UAM (Urban Air Mobility) kommer drönare att behöva integreras med lokala samhällen, städer och regioner på ett sätt som maximerar nyttan och minimerar negativa konsekvenser. Att hantera buller från ett transportsystem med drönare kan vara avgörande för drönartjänsters framgång. Om buller och störningar inte beaktas finns det risk att förverkligande av dessa innovationer försenas eller försvåras av begränsningar i planerings- och tillståndsprocesser, eller att restriktioner åläggs verksamheter.

APIS-projektet syftar till att öka medvetenheten, utveckla kunskap och tillhandahålla metoder som stödjer en **ordentlig** utveckling och implementering av drönare. APIS-verktyg och metoder adresserar specifikt buller och störningar genom utvecklingen av en simuleringsplattform SAFTu och ett konceptuellt ramverk för implementering av drönare i en urban miljö. Projektet har genomförts med ett brett synsätt inklusive att engagera intressenter i diskussioner och intervjuer med Trafikverket, Stockholms stad, regioner, Transportstyrelsen, LFV, tillverkare och intresseorganisationer.

En central leverans av projektet är SAFTu-programvaran för simulering och prediktering av buller. Detta verktyg gör det möjligt att beräkna bullernivåerna på marken från UAV-trafik (Unmanned Aerial Vehicle). Ljudnivåkonturer baserade på olika mätetal kan beräknas och visas på en karta. Antalet invånare som exponeras för bullernivåer inom ett ljudnivåband presenteras i histogramform. Ett ramverk för bestämning och implementering av UAV-ljudkällmodeller i SAFTu har utvecklats. Två olika leverans-UAV, baserade på uppmätta bullerdata, har implementerats i SAFTu:s bullermodeller tillsammans med metodik för att lägga till fler UAV källor.

Två scenarier för drönartjänster i Stockholmsregionen och i Jämtlands län behandlas, vilka representerar potentiella implementeringar av UAM för godstransporter. SAFTu används för att bedöma ljudnivåer och i ett fall antalet utsatta invånare.

Två scenarier för implementering av ett drönarsystem i olika omfattning i stadsmiljö, har analyserats med avseende på avvägningar mellan måluppfyllelse och förutsättningar för innovation. Det finns för- och nackdelar med båda scenarierna som är svårbedömda med komplexa samband. Dessa samband beskrivs i det konceptuella ramverket för implementering av UAM (WP1).

En rekommendation är att SAFTu bullersimuleringar används för att utvärdera bullereffekter relaterade till val av UAV-typ och planerad drift och även för att optimera flygrutter. Simuleringar kan också användas för att kommunicera effekten av införande av drönare och buller-bekämpningsåtgärder till berörda medborgare samt i utbildnings- och kommunikationssyfte som kan främja kompetens-utveckling hos aktörer och acceptans i samhället.

Det bör noteras att beräkning av buller från UAV-flygningar på marken inte kan hanteras av nuvarande flygplansbullerkartläggningsstandarder (som ECAC Doc.29-metoden). Inte heller kan typiska verktyg för omgivningsljud, riktade mot väg och järnvägstrafik, korrekt hantera för flygande farkoster/ljudkällor. Så för att fastställa möjlig framtida UAM-bulleravtryck behövs nya verktyg som SAFTu.

Med utgångspunkt i projektets resultat och tidigare erfarenheter konstateras också att det behövs utveckling av bullerregler och riktlinjer för drönarverksamhet. För att stödja införandet av UAM i Sverige behövs också mer forskning inom detta område både vad gäller noggrann bullermodellering och analysmetodik samt metoder för att minimera akustisk störning.

Content

1 Project description

APIS is a two-year project performed at KTH (2023-2024). It was funded by TRV's Aviation Portfolio and initiated from a call by KTH CSA (Center for Sustainable Aviation) with a primary focus to support research on aviation noise issues. The project is called APIS and consists of an acoustic part and an implementation part focusing on the noise propagation and associated disturbance caused by drones when introduced into urban environments. Further, a system analysis and problem formulation were performed for the coming implementation and integration of a new mode of transportation into an urban context, such as a municipality like Stockholm. This project report summarizes information from APIS interim reports and publications (Orrenius et al. 2024; Ulfvengren et al., 2024; Ulfvengren, 2024 a; Ulfvengren, 2024 b, and Ulfvengren, 2025).

APIS has been carried out in collaboration between INDEK at KTH school of Industrial Engineering and Management (ITM), MWL at KTH school of Engineering Sciences (SCI), Akustikdoktorn Sweden AB, and Aurskall Akustik AB and IBG (Independent Business Group) The reference group for the project had representation from EASA, TRV, TS (Transportstyrelsen, Swedish transportation authority), LFV, NV (Naturvårdsverket - Swedish environmental protection agency) and KI (Karolinska institute, environmental medicine). The project group consists of people with complementary experience and knowledge: Ulf Orrenius (Akustikdoktorn Sweden AB) and Ulf Tengzelius (Aurskall AB) are industrial researchers and acoustic experts with practical experience of aircraft noise sources, environmental noise and modelling of noise emissions; Mats Åbom (KTH) is a senior researcher with a focus on aeroacoustics, noise sources like propellers and rotors and with experience of aircraft noise, Pernilla Ulfvengren (KTH) is an associate professor in industrial engineering and management with expertise in sociotechnical systems with experience from aviation operations and noise issues, and Jan-Olof Ehk with many years of international experience in aviation safety, future airspace and in particular knowledge of drones' airspace development.

The project background concerned noise issues as a potential consequence of implementing drones into an urban setting, and ultimately an Urban Air Mobility (UAM) system. Two main areas were identified. One was to develop knowledge of drone sound sources and to simulate noise exposure footprints. The other was to understand the receiving system into which UAM is implemented to. The synthesis of the two studied areas was intended to identify functions in which noise simulations could be applied and useful in planning- and decision processes, and in assessing environmental consequences. Aviation noise issues have been studied in earlier research projects. In INFRA, noise issues between air operations and citizens exposed to aviation noise was studied (Ulfvengren, 2023) and in SAFT, a tool for noise simulations of conventional aircrafts was developed (Tengzelius, 2019). APIS builds on a joint continuation of those research projects.

The overall objectives of the APIS project have been to (i) develop SAFT to become accessible to analysts and decision makers in need of noise simulations in aviation and integrated transportation systems; (ii) establish a new platform SAFTu, supporting decision making for future air traffic noise analyses, including UAVs; (iii) identify critical sociotechnical aspects in implementation of drones in urban areas and implementation guidance to central stakeholders and, (iv) collaborate with stakeholders and identify and provide an initial evaluation of measures for noise and annoyance mitigation strategies.

The APIS work was organised in five work packages (WPs):

WP1 System description, stakeholder needs and implementation framework. WP1 addressed the envisioned transportation and implementation system including investigating city planning processes and regulations for drone operations and best practice in noise annoyance mitigation strategies.

WP2 - SAFTu development for usability and functionality. WP2 dealt with prediction methods, specifically (i) adapting the present SAFT methodology and code for future aircraft, like drones and electrical aircraft and (ii) to establish a validated and well documented platform based on SAFT for analysing effects of variations in flight routes and airframe settings at different atmospheric conditions. The code was developed and adapted to facilitate user needs.

WP3 - SAFTu applied to APIS scenarios- applicability study for UAVs. In WP3 SAFTu was tested and applied using the developed code for assessment of drone operations. A hypothetical drone urban landing area (vertiport) and drone service case was analysed with respect to noise impact of the people living in the surrounding area. Scenarios were analysed of how choice of flight path, acoustic measures at the vertiport, frequency of drone landing and take-off affect noise exposure.

WP4 - *Noise impact metrics, measures, scenarios and evaluation.* In WP4 noise associated annoyance from drone operation was analysed with respect to drone operation for people affected both on technical level and with respect to society level. Measures for mitigation and control were identified, including effective acoustic specification recommendations of new UAVs and the potential effect of noise control measures on novel vertiport installations.

WP5 was dedicated to project management and dissemination of the project results (reporting, seminars, SAFTu Software manual).

2 Dissemination

During the project, we have published four conference papers and presented APIS at two of KTH's CSA annual seminars. We have presented project results for the Swedish Transport Association's network of manufacturers and operators as well as for SKR's drone network and conducted a half-day training/seminar for 35 municipalities and regional representatives. The seminar was recorded and has been made available to all municipalities and regions (SKR).

APIS has also been presented at:

- EU transport delegation when visiting KTH
- TRV/LFV's automation days in Kista
- CityAM's drone gatherings, in collaboration with Kista science city
- KTH Digital future drones WS.

During the project, we conducted three reference group meetings and had monthly recorded project work meetings.

2.1 Publications

[1] Orrenius, U. Tengzelius, U. Ulfvengren, P. Ehk, J-O and Åbom. M. (2024). Noise simulation for UAM integration- Application to a health-care logistics system, in Proceedings of the 2024 DICUAM Delft International Conference on Urban Air-Mobility, Delft, The Netherlands, March 2024.

[2] Ulfvengren, P., Orrenius, U. Tengzelius, U., Ehk J-O. and Åbom, M. (2024). UAM system integration - System analysis and noise simulations in support of regional and city planning, in Proceedings of the 2024 DICUAM Delft Int. Conference on Urban Air-Mobility, Delft, The Netherlands, March 2024.

[3] Ulfvengren, P. (2024) UAM innovation – a sustainable transition? R&D management conference. KTH Royal Institute of Technology, June 2024

[4] Ulfvengren, P. (2024) Noise in sustainable transformation of aviation, NOISECON, New Orleans, 2024

[5] Ulfvengren, P. (2025) När flyget kommer till stan! Interim report APIS project TRV 2022/106395. KTH TRITA-ITM-RP 2025:1

[6] Ulfvengren, P., Orrenius, U. Tengzelius, U., Ehk J-O. and Åbom, M. (2025) APIS Final Report, TRV 2022/106395.

[7] Tengzelius, U., Orrenius, U. (2025), SAFTu user's manual.

2.1.1 Students' reports

Knowledge has also been disseminated during a total of three course rounds with fifth-year students in the I-programme at KTH who have worked with different drone scenarios in their projects with titles such as:

- Analys av det kommersiella intresset för införande av drönare för leveranser på regional nivå
- Drönares potential som substitut till ambulanshelikoptrar
- Optimal battery selection for last-mile delivery drones
- eVTOL Air Taxis: A Comparative Analysis of Emerging Urban Mobility in Sweden
- Cost-benefit analysis of vertiport development in Kiruna municipality
- A Decision Framework for Last-mile-delivery Solutions
- Connecting the Archipelago: Balancing Noise Mitigation and Operational Efficiency in Drone Deliveries
- Integrating Drone Technology for Last-Mile Delivery: A Scenario-Based Analysis for Rural Logistics
- Key trade-offs associated with scaling UAV-based agricultural systems in urban environments

3 Project results

In view of the character and scope of the APIS project, the results can be split into two main areas:

- System level analysis and problem formulation regarding implementation of UAM. A "concept of operation" (CONOPS) for UAM in Swedish municipalities including a trade-off analysis between two scenarios for UAM implementation at different scales, resulted in a conceptual framework of sociotechnical aspects in relation to UAM implementation.
- Method development for assessment of drone noise implemented in SAFTu, a noise prediction software for UAM including vehicle noise source representations, noise propagation and noise mapping

In the next chapters the results are presented regarding findings from the literature and from interviews, methods and concepts developed and analysis of findings from the studied scenarios and use cases. The following areas are presented with a separate chapter: (i) state of art perception studies of drone noise, (ii) development of the SAFTu platform for noise predictions, (iii) source modelling related to UAVs and air-taxis, (iv) computation of sound propagation (v) use cases analysed for package delivery UAVs, (vi) system analysis, problem formulation and implementation and (vii) mitigation of drone noise. In addition, recommendations for different stakeholder groups in view of the project results, and for future research, are presented.

4 State of art - perception of drone noise

4.1 Drone noise in relation to conventional aircraft and road traffic

The character of drone noise is very different from existing helicopters and small airplanes. For smaller UAV's the emitted sound power is orders of magnitude lower than for large aircraft and today's helicopters. For passenger VTOL's we can expect lower noise levels compared to current helicopters, ~10 dB lower noise emissions indicated from our comparison of with an acoustically optimized eVTOL (Joby) vs. similar size helicopter at take-off and landing (during level flight ~20 dB lower). However, if UAV air traffic becomes denser and closer to residents it may be perceived as unacceptable. The reason why noise is viewed as critical is that sound from drones is often of a disturbing character which could hinder the integration of Urban Air Mobility (UAM) into transportation systems (Cohen et al., 2021; NASA, 2020; Holden et al., 2016).

In an acceptance study (EASA, 2021), results show, like other studies, that we experience noise from aircraft as more disturbing than other sound sources with the same noise level (WHO, 2018). EASA's report states that familiar sounds are more accepted than new types of sounds. With this logic, the authors express hope that some habituation will occur over time, meaning that IAM will be perceived as less disturbing over time. Humans are indeed adaptable, but there is no evidence in sound perception studies reviewed in this project indicating that humans perceive road traffic noise, as less disturbing because we are more used to them than we are to noise produced by the air transportation system.

The literature on the effects of drone noise is limited (Schäfer et al., 2021) but new studies are underway. The available results present a consistent picture, showing that drone noise is significantly more disturbing than that from road traffic and aircraft. The main reason given is drones' specific acoustic properties, especially their pure tones and high-frequency broadband noise. One study (Gwak et al., 2020) indicates that a large drone should operate at a noise level 10 dB below that of an airplane to be perceived as less disturbing. Similarly, a large drone needs to be at a 6 dB lower level to be less disturbing than a small drone. A large drone is perceived as equally disturbing as an airplane if it is at a 4 dB lower level than the airplane. This provides an indication of how much more disturbing drone noise is perceived.

4.2 Design of low annoyance drones

Designers, developers and operators of drones should be aware of how choices in design may affect a particular drone service potential to be accepted on a broad scale. For example, drones with wings can be made substantially more silent than those without, moreover rotor size, pitch and distance to the airframe and adjacent rotors should be considered. In addition, symmetries and regularity is not always optimal due to rotors aeroacoustic interaction (Smith, 2020).

Few studies are publicly available in which manufacturers have experimented with design to affect how drone noise is perceived. Increasing weight of the UAV tends to increase the noise level, but one should remember that if the tonality is reduced, often not measured, may make up for the increase in noise level of larger drones. In theory, a larger drone with a design which gives it less disturbing tonality could be perceived less disturbing than a smaller drone. Pure tones and high frequency tones are also parameters mentioned that contribute specifically to annoyance.

To address other noise issues than sound pressure level an approach called "experience-based" design is suggested with the objective to attain acoustically optimized drones. This was tested in a successful trial of Australian drone service with thousands of deliveries with very few complaints (Burgess, 2020).

Uber Elevate set a goal for VTOL vehicles operating from vertiports/stops given that drones are expected to be more annoying than existing road traffic. They suggest that drones should ultimately approach noise levels (exposure at the front of the nearest residence) half that of a truck traveling on a residential road (75-80 dB(A) at 50 feet): approximately 62 dB L_{Amax} at 500 ft altitude. However, as they note this is about one-fourth as loud as the smallest four-seat helicopter currently on the market at the time of the study (Holden et al., 2016).

Future designers, developers and operators of drones should be aware of how choices in design may affect a particular drone service potential to be accepted on a broad scale. For example, drones with wings can be made substantially more silent than those without, moreover rotor size, pitch and distance to the airframe and adjacent rotors should be considered. In addition, symmetries and regularity is not always optimal due to rotors aeroacoustic interaction (Smith, 2020).

4.3 Methodology for annoyance assessment

In literature, perception results are mainly reported from laboratory studies. Such studies are experience-based subjective assessments and cannot provide insights into impacts on well-being and health (Fastl and Zwicker, 2007). In listening studies, it can be observed that sound levels affect the degree of disturbance. However, methods for comparing conventional airplanes and helicopters are not considered to apply to drone noise. In today's aviation, sound pressure levels (dBA) have correlated well with variations in the number or magnitude of noise events. One challenge for drones is that different designs and constructions produce fundamentally different sound profiles. Drones with different designs will vary in both spectral and temporal characteristics. Thus, new metrics are probably needed as drone noise differs in more ways than just sound pressure.

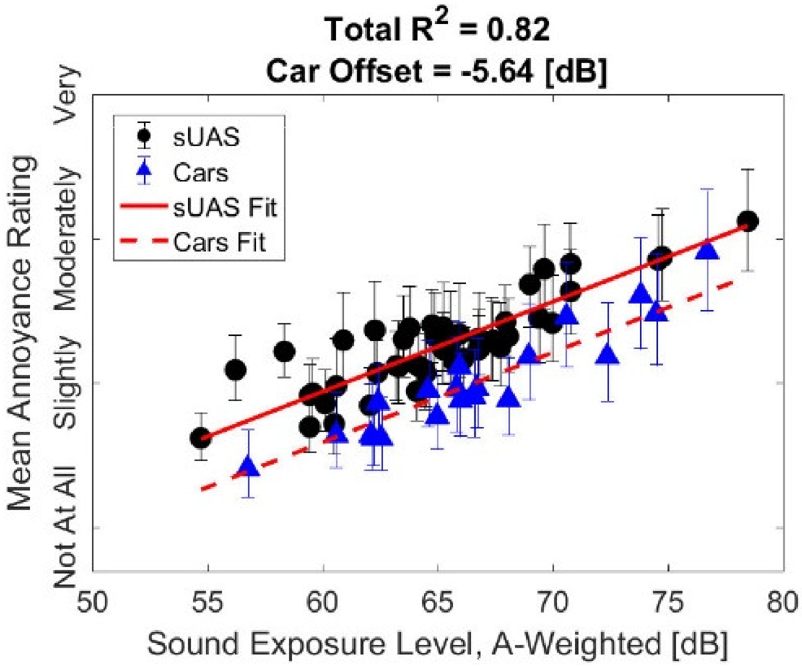

Figure 1. Mean annoyance rating from listener tests of noises from small UAVs and cars (delivery vehicles). Different Sound Exposure levels are compared with the UAV noise being on average perceived as having the same annoyance as that from cars with 5.6 dBA lower sound exposure level. More details are given in reference (Christian and Cabell, 2017).

Humans can notice when two sound sources are perceived as equally disturbing. For example, a test showed that drones are perceived as equally disturbing as a typical (American) delivery vehicle with a 5,6 dB higher sound level (Christian and Cabell, 2017; Christian, 2018). Another test (Torija and Li, 2020) showed that when comparing the same sound profile with and without drones, disturbance increased with drones even if the background noise was road traffic noise at a higher sound level than the drone noise. The same study also revealed that disturbance from a quadcopter was greater than from a jet aircraft. Psychoacoustic parameters that can contribute to understanding noise disturbance from drones vary. For instance, parameters like loudness, sharpness, roughness, fluctuation, strength, and tonality are relevant for describing how a sound's characteristics are perceived (Fastl et al., 2007; Nordtest, 2002). Differences in tonality, for example, can make one drone more disturbing than another.

4.4 Annoyance aspect of UAM integration in cities

One approach to mitigate drone noise annoyance is that of masking. One idea is that background noise from road traffic could mask the drone noise and thereby reduce its relative contribution to the ambient noise levels and associated annoyance. However, this reasoning could potentially be "abused" to concentrate new sources like UAM at already noisy areas, which will increase noise for those already exposed to road traffic if drone noise characteristics stick out. An acoustically sound idea could thus be perceived as an unjust or undiplomatic approach considering the exposed citizens' perspective.

In studies examining health effects, models exist suggesting a balance and a level of noise acceptance can be found. Above a threshold, sound is perceived as an intrusion in an already noisy environment, but if maintained within levels that do not stand out in the environment, acceptance can be achieved. (Begault, 2021; NASA, 2020)

5 Development of the SAFTu platform

The SAFTu software is based on its predecessor SAFT (Tengzelius, 2019; Tengzelius 2021) Both codes are based on so-called simulation methods which, in contrary to the older “integrated methods” like INM and ECAC Doc.29, include a separation of the sound source and the propagation, respectively, giving the possibility to study moving vehicles/sound sources with arbitrary characteristics regarding sound source strength, directivity and frequency characteristics. Moreover, SAFTu allows for ray-tracing sound propagation methods, and different atmospheric models and conditions may be applied. The fundamental output, noise level contours on a map over the studied region, can be determined and displayed based on most existing noise metrics. This is made possible since a time-frequency history can be calculated in all ground grid points. The frequency is given in 1/3-octave bands.

The SAFTu methods are primarily developed for parameter studies in the case of single flight-events but may also be applied for UAM air-traffic scenarios.

SAFTu is designed with simplicity in mind regarding input and effectivity in terms of computational speed. Currently an interactive input in a serial manner is followed: vehicle/source, region (within Europe), ground track, profile (including flight mode, e.g. “copter”, “fixed wing” or “transition/mixed”, when necessary). The flow chart for a SAFTu run in the case of noise contour mapping is illustrated in

Figure 2 below. The outputs in green are noise contour maps and histograms providing an estimate of the number of people exposed to levels within noise level bands.

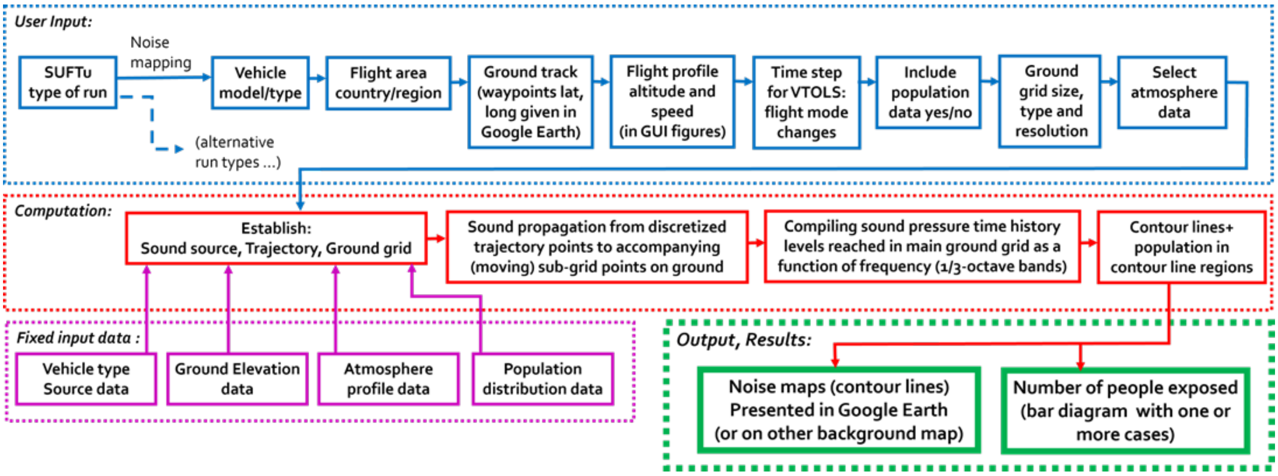

Figure 2. Process flow chart for running SAFTu to produce noise maps from a given UAV flight. From the SAFTu manual (Tengzelius et al 2025).

Based on user given input data and previously established fixed data, such as ground topography (DEM – Digital Elevation Model), a 2D ground grid following the terrain is computed before the main computation starts. This involves a discretization of the position of the vehicle (sound source) along the trajectory where the emission of sound rays to the ground grid points takes place. Here, the number of sound-rays/receiving points is limited to those that significantly contribute to the resulting sound level on the ground. This method with a “moving small-sized sub-grid" below the source, is very effective, resulting in a typical computational time in the order of minutes, depending on flight path distance, sound source strength, and wanted resolutions of trajectory and ground grid.

In SAFTu, the source is either represented by a monopole with uniform sound radiation, in all directions, or by the sound intensity it emits in different directions at the radius of 1 m[1].

In addition to the standard noise level contours, SAFTu may also produce ΔdB contours, i.e. contour curves representing differences between two different cases, for example different vehicle types flying the same route, variation of altitude or different operating procedures for the same vehicle type, …etc. (figure 3).

Another added functionality is the estimation of population numbers found within discrete dB-bands, say 10 dB bands as: 45-55 dB, 55-65 dB, …. The number of inhabitants exposed to noise in a certain noise level band is displayed as bar charts for one, two or more scenarios representing different flightpaths/vehicle types/procedures/flight profiles/…(figure 4),

A manual describing the underlying calculation methods, interfaces to external databases and tools, and the use of SAFTu, has been established (Tengzelius, 2025).

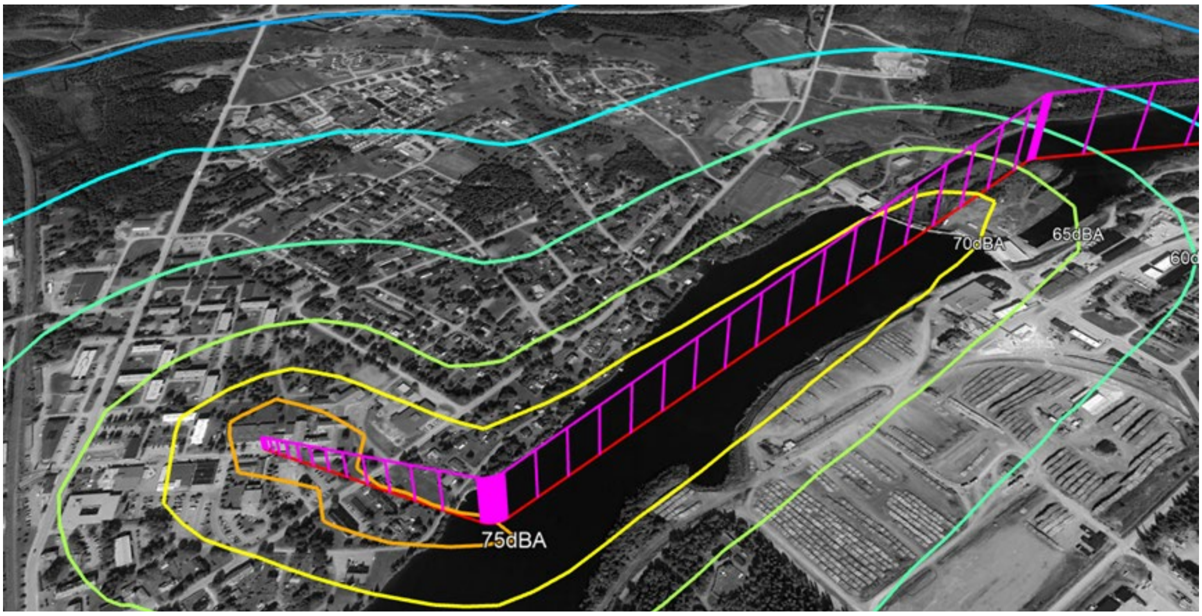

Figure 3. Example SAFTu run output showing vehicle trajectory (magenta), ground track (red) and resulting $L_{A,max}$ *noise contours (orange = 75dBA, yellow= 70dBA, ...) for a flight with a 40 kg VTOL.*
Note: the vertical *magenta-coloured* lines denote discretisation/time steps from which noise emission is computed.

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[1] The sound intensity for an acoustic source in a free space is the sound power per unit area. Integrating the intensity over the area of the sphere gives the total sound power of the source. A common approximation in the field of aircraft noise propagation is that aircraft/sound sources are represented by a point source with source strength given as sound intensity at 1 m, this is also the case in SAFTu.

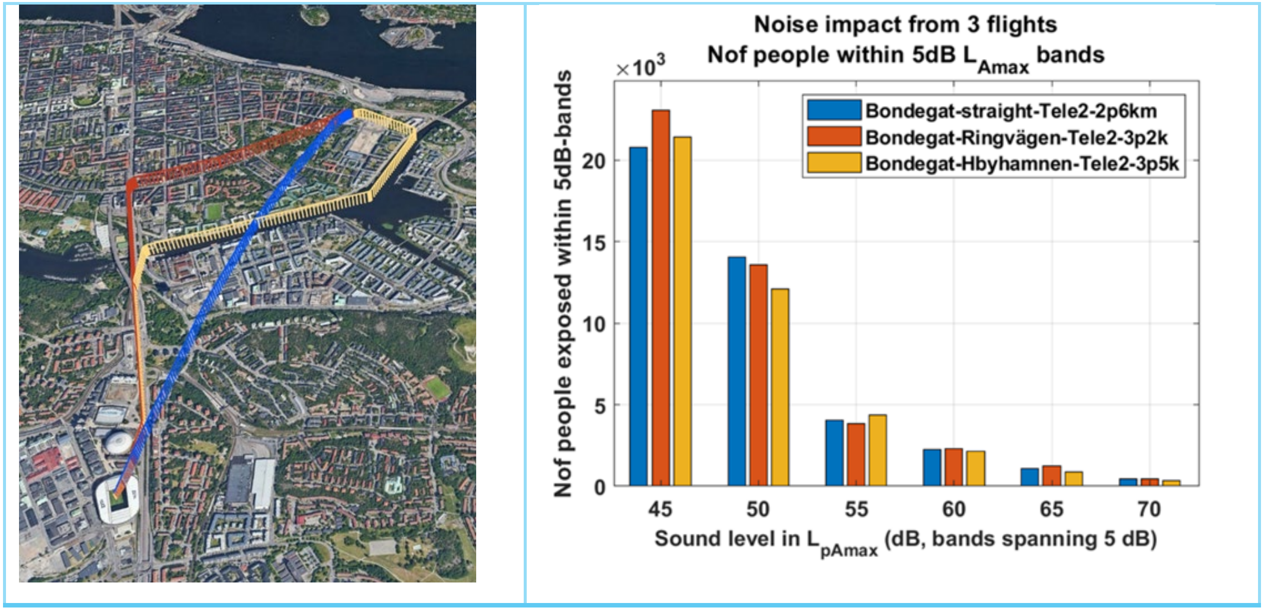

Figure 4 Left: Example of three different flight trajectories in SAFTu between Bondegatan and Tele2 arena in Stockholm. Right: Number of people exposed for different $L_{A,max}$ noise levels

6 Source modelling for UAVs

Predictive noise mapping from air traffic relies on estimating the sound sources of the vehicles. Without accurate models of these sources, the noise levels on the ground can't be trusted. In programs like SAFTu, UAV noise source strength and character representations must consider vehicle type and size, flight mode, rotor type and rpm for thrust and lift generation.

6.1 Categorization of drones and VTOLs

Although a wide range of UAV concepts exist, as discussed in e.g. Rizzi et al. (2020), we choose here to categorize them into two groups regarding noise generation: VTOLs or multicopters. Here VTOLs denote vehicles equipped with fixed wings for creating lift (forces) during cruise/level flight and horizontal rotors for lift generation during hover and vertical take-off/landing. Within the group "multicopters" we address vehicles, without wings, which utilize rotors to generate both lift and thrust for forward propulsion.

It can be noted that VTOLs either apply tilting proprotors (90°) or two different sets of rotors when going to/from level flight and landing/take-off.

6.2 Point source models

When computing noise emission and propagation from static or moving sound sources like UAVs, a common simplification is to represent the vehicle as a so-called *point source*. This approach is also applied in within SAFTu. In this mathematical idealisation the vehicle is represented *by an infinitely small source radiating sound in all directions*. The sound radiation is usually given as equal sound intensity (sound power/unit area) in all the directions but can also be set according to a certain directivity pattern where the intensity varies with polar angles q, j. Typically, the source strength is set as sound intensity at 1m and q is defined as 0° pointing forward in the x - "aircraft nose" direction and 180° pointing backwards. j usually set as 0° point along the y- "right wing" direction and 90° downward (z-direction in the aircraft coordinates). This zero-extension source model works well if the distance to the receiver is large enough and not in the same order as the source/vehicle itself, see Figure 7 for coordinate systems etc.

In SAFTu the vehicle sound source intensity, as well as receiving point sound pressure levels, are given as functions of time and frequency. The frequency is given in 1/3-octave bands.

With a defined (point) source, with uniform- (monopole) or any directive characteristics, one can, as in SAFTu, couple this source model to the sound propagation in the computational chain towards the resulting noise time histories in receiving points on ground.

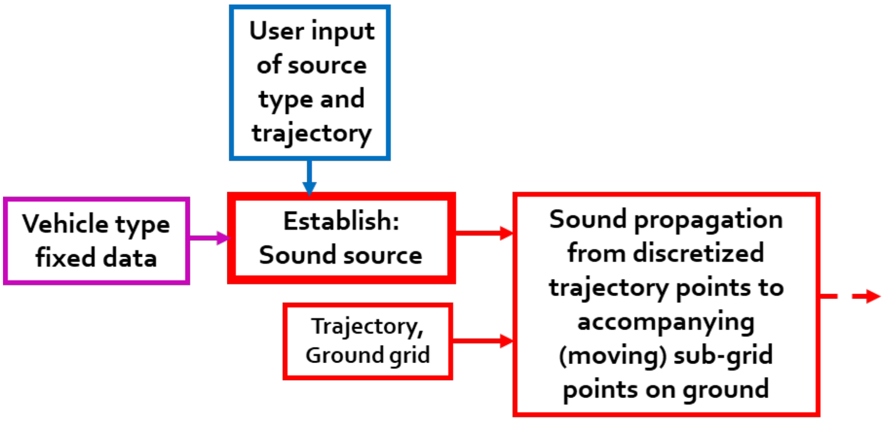

Figure 5 Vehicle sound source representation in SAFTu flow chart logics

6.3 Sound source characteristics, dependencies and modelling

According to literature on Urban Air Mobility (UAM), future vehicle fleets are anticipated to be equipped with propellers or rotors powered by electric motors. As a result, aerodynamic flow induced rotor noise is expected to dominate the total noise emission and impact[1].

Based on physical mechanisms and how aeroacoustic noise is generated, the rotor noise can be classified into either *thickness, loading or high-speed-impulsive noise* (Greenwood et al, 2022) (definitions/mechanisms described by the Ffowcs Williams and Hawkings, FW-H, equation) and characterised as follows (see figure 6):

<u>Blade Loading Noise:</u>

Caused by periodic variations in the aerodynamic loading forces of the blades as they rotate. Related to lift and thrust generated by the blades. Shows typically a great similarity with the mathematical abstraction model: dipole (which can be seen as two monopoles infinitesimally close with equal strength oscillating in opposite phase, resulting in a directive source with the shape of a "8". With the narrow waist in the plane of the rotor, increasingly expressed with higher frequencies) – *expected to dominate for UAVs*.

<u>Thickness Noise:</u>

Caused by the displacement of air mass due to the motion of the blades. Linked to the speed and size of the rotor or propeller. - *Not expected to be as loud as blade loading noise for UAVs*

<u>High-Speed Impulsive (HSI) Noise:</u>

Arises when blade tips approach or exceed the speed of sound. Highly nonlinear and generates intense noise (shock waves). Common in fast-rotating blades or during high-speed forward flight. – *Not expected in UAVs with lower blade tip speeds than most helicopters.*

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[1] *The same would generally be the case also for rotor-craft equipped with combustion engines, assuming that the engines are equipped with standard silencers, most probable the same vehicle but with electrical motor replaced with a combustion engine would be quieter. This since the power source, e.g. kerosene, would have less mass due to a higher fuel density compared with the batteries. I.e. the battery powered vehicle would need more lifting power and in turn create more sound power*

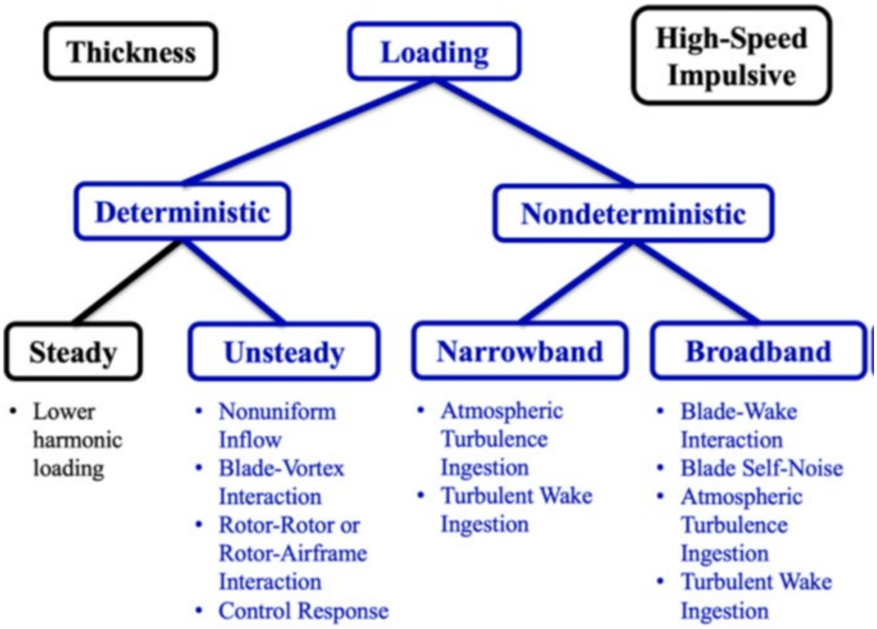

Figure 6. Rotor noise origin characterisation. From (Greenwwod et al, 2022)

In summary, unsteady loading noise is likely the main concern for typical UAVs. Moreover, the pattern often seen in helicopter noise data with maximum sound levels found during descent due to strong blade-vortex-interaction (BVI) tend to be less pronounced for VTOLs according to comparison of Joby and helicopter noise data for different flight modes (Greenwood et al, 2022).

Though, solving the FW-H equation for a single vehicle/flight/atmosphere condition exceeds the APIS budget by far. Therefore, in SAFTu we must rely on established noise source data and empirical estimations based on literature or measurement data directly from manufacturers. Engineering methods are applied to turn these data into SAFTu sound source representations.

The need for measurements to establish sound source models gets even more clear accounting for the complexity linked with a computational path:

A) Different flight modes (categorical sound source variables) like hover, climb, transition, cruise and descent, each with different noise generation mechanisms + varying continuous predictor variables within those modes, e.g. speed, rotor rpm and relative phases.

B) Even with Computational Aeroacoustics (CAA) resources at hand typically the results must be validated against measurements. Additionally, accuracy in CAA studies shows in general greater variation and lower accuracy compared to other scientific acoustic disciplines. Noise during descent and transition is particularly difficult to predict due to unsteady aerodynamics and complex rotor-vortex interactions (Marques et.al. 2024).

In terms of spectral characteristics drone noise spectra typically consist of prominent tonal components in the low-to-mid frequency region, broadband noise in the mid-to-high frequency region, and electric motor noise in the high-frequency region. The relative strength of each of these components varies depending on the UAV size (Ramos-Romero. et al. 2023)

The sound radiation directivity found in multicopter measurements often shows a rather different pattern compared with an idealised dipole model, while multipole expansions can give a better resemblance to measurements. This situation related to simpler and even more advanced analytical models together with the computational cost and limited accuracy in absolute levels from CAA-modelling, makes measurements, if possible, with added multi pole expansions or spherical harmonics, the most reliable way to estimate UAS as sound sources and their directivity today.

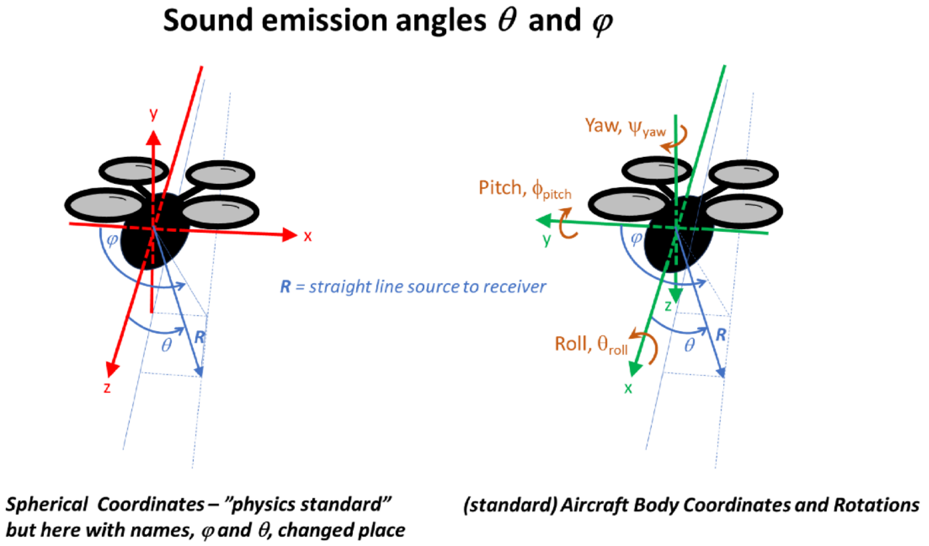

Figure 7 Coordinates and polar angles for directivity applied in SAFTu.

Good examples of quadcopter noise characteristics, including directivity, for a stationary source/vehicle in an acoustic lab is given in: A) (Alkmim et al., 2022) and B) (Heutschi et al., 2020).

In A) Measured spectra and directivities based on those (+multipole expansion) are presented for a small drone, 1.2 kg, for a few different values of rpm are shown in Figure 8 below.

The complexity of UAV noise modelling may be even more emphasised accounting for rotor pitch, air inflow speed and direction, individual rotors rotation direction and relative phase, flow interaction with rotors and main vehicle structure etc.

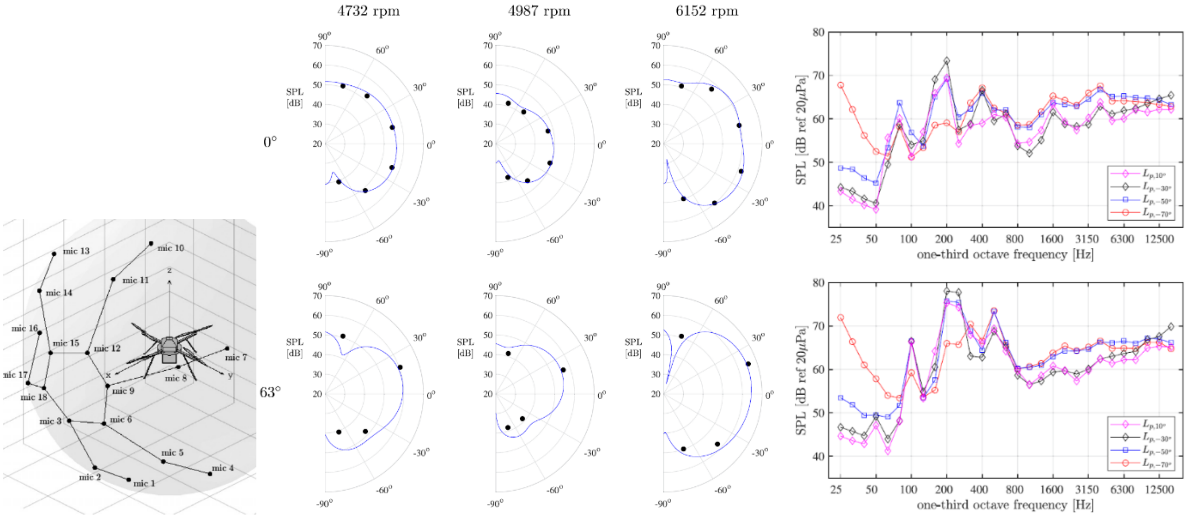

Figure 8 Left: Mic. array setup; Center: Sound pressure levels in polar coordinates as a function of elevation (φ as of Figure 7) at 0° and 63° azimuth (θ as of Figure 7) Solid blue line, derived from third order spherical harmonic reconstruction; solid dots, experimental data for 4732, 4987, and 6152 rpm at their respective BPFs; Right: SPL in 1/3-octave bands at elevation, (φ as of Figure 7) 10° -30° -500° and 70°,) (Alkmim e al., 2022).

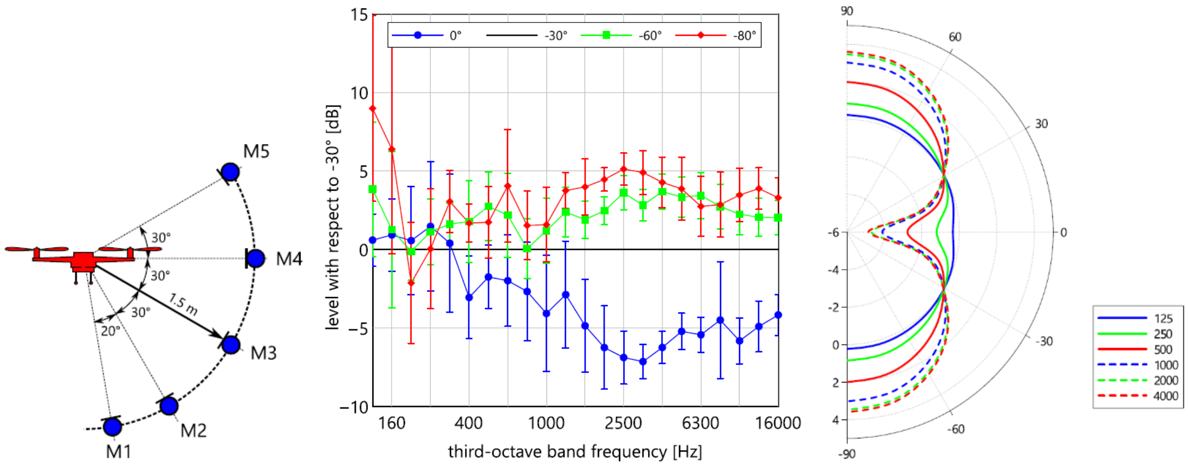

Figure 9. Left: mic set up; Center: Average spectral differences of the radiation strength in the directions 0°, -60° and -80° with respect to the reference direction -30°, SPL mean over 5 studied multicopter models; Right: A second order filter ("high-shelving") forced to fit to the mean directivity as shown in fig b. (Heutschi, K. et al., 2020)

6.4 Sound sources in SAFTu

The empirically established vehicle sound sources in SAFTu are in the range from “small” quadcopter (ca 1kg) over delivery eVTOLs (10-50 kg) to eVTOL for passenger transport. The sources are based on lab/field measurement data or other estimates given in the literature or reported from manufacturers.

Quadcopter ca 1kg

The first example is the ca 1kg DJI Phantom II quadcopter, could be seen as a typical hobby/photo-drone (Note: slightly outdated, not on the market anymore). In reference (Intaratep et al. 2016) results from measurements of thrust and sound in an anechoic chamber were made to study its aeroacoustics performance. We used the sound spectral data at different thrust/rotational speed from published data (graphical representations) to set up a simple source model as in Figure 11. With support of flight dynamics models (Chen et al, 2018) estimates of lift and thrust forces based on user trajectory profile input (position + speed) are used to get approximate rpm and from rpm noise intensity emissions by interpolation from the two 1/3-octave spectrum to the right in Figure 11. In this case the source is approximated as omnidirectional, i.e. without any directivity

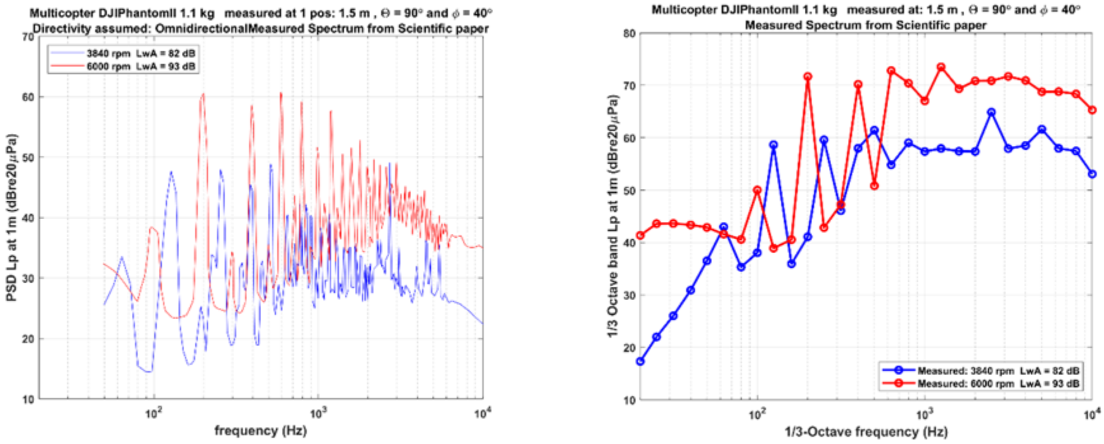

Figure 10. DJI Phantom II spectrum, Left: Power Spectral Density; Right: 1/3-octaves applied in SAFTu. (Chen et al, 2018)

eVTOLs 20 kg, 40 kg:

VTOLs noise source models must handle at least two different flight modes, vertical and horizontal (level) flight respectively. This 90-degree transition between vertical take-off and landing to forward fixed-wing flight is typically managed either by tiltrotors or, typically in the case of smaller VTOLs, by separate fixed rotors and motors that are sequentially activated or deactivated with some overlap.

For two implemented delivery eVTOLs, 20 kg and 40 kg maximum take-off load (MTOL) respectively the noise sources are applied based on measurement data, outdoor field measurements and for the smaller also lab measurements. In case of the 20 kg UAV, two different models regarding rotor variants are implemented. Here the one with larger size propellers/lower pitch and rpm, tend to give lower total noise levels, both at source and on ground.

For both vehicles the position(s) along the flightpath for where these flight mode changes take place must be set (either manually or by a simple speed and ascent-/descent angle criteria).

For each flight mode (conditional/categorical variable) a trimmed, fixed level, third octave spectrum is established. These spectra are based on measured total sound levels, a BPF (Blade Passage Frequency), frequency-peaks widths (“Q-values”) and assumed amplitude slopes. The amplitudes are trimmed to agree with measured total sound source pressure levels. Sound intensities at 1 m are finally established to represent input sound sources. Currently omnidirectional sources are assumed (though a directivity could be added).

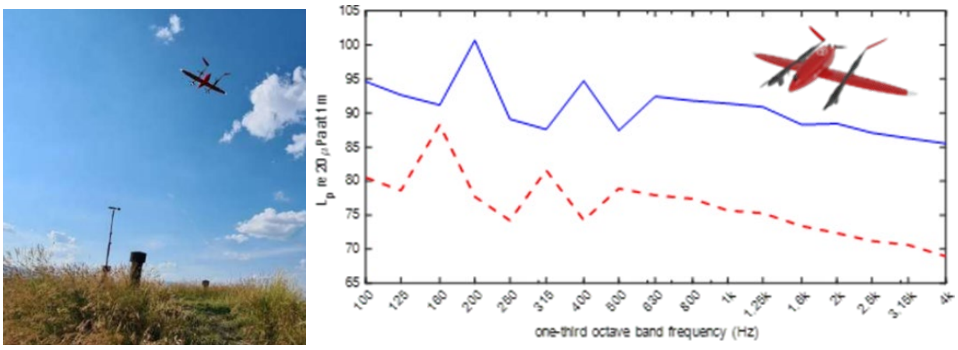

Figure 11 Left: Measurements of sound levels according to EASA guidelines (EASA, 2022). Right: Downward sound pressure levels at 1 m from the vertical (——) and the horizontal (--------) propulsion units in 1/3-octave bands. Spectra are tuned to field-measured overall levels for the example UAV (Orrenius et al, 2024).

<u>UAS max 4 kg EASA Max sound power level Regulation 2019/945:</u>

For smaller drones, up to max mass of 4 kg, EU-regulations (EASA) are setting a limit of max 93 dBA emitted A-weighted sound power level, L_{WA}, re $W_0 = 10^{-12}$ Watt. For smaller drones with $m < 0.9$ kg the max allowed $L_{WAmax} = 81$ dBA and in the span $0.9 < m < 4$ kg given by: $L_{WAmax} = 81 + 18.5\log(m/0.9)$ dBA. These levels are a mandatory threshold that manufacturers must meet for certification and market access in the EU.

Based on this regulation limits + typical multicopter spectra given in (Heutchi et al., 2021) scaled sound sources can be established and run in noise mapping cases with SAFTu.

<u>Passenger transport VTOLs:</u>

In (Koehler et al., 2021) a simplified source representing a passenger eVTOL is applied. The sound emission spectra presented therein for the tree flight modes “Take Off/Hover”, “Hover/Transition” and “Cruise Mode” are applied as an alternative within SAFTu.

We have also started work with SAFTu VTOL and Helicopter noise sources (e.g. Joby eVTOL) but this has to be considered as "ongoing" since the full chain from flight procedures/source establishment is not yet in place and possible to run.

General source defined by user:

This functionality is aimed at setting up a sound source tailored by the user regarding source strength and directivity. Input data could be taken from theoretical analyses, measurements or changes with regard to known source data that are of interest to study in terms of noise contours or resulting noise time histories in receiving points on ground.

Figure 12. Picture of Jobi air-taxi showing the tilting rotor system (K. Pascioni et al, 2022)

7 Computation of sound propagation

7.1 Overview of methodologies

In aircraft/UAM noise simulation and noise mapping programs like SAFTu, the sound source representation is coupled as input to the noise propagation model (Figure 2 and Figure 5).

There are two main computational approaches for modelling noise propagation through the atmosphere: ray-tracing and field methods.

The field methods involve solutions of the full wave equations in a continuous atmosphere, usually simplified to 2D fields and solved by parabolic equation methods, finite element or boundary element methods. These methods can account for interference, diffraction, refraction in complex environments but become usually to computationally heavy for moving sources (aircraft/UAVs).

Ray-tracing (geometrical acoustics) on the other hand assume some simplifications leading to a computationally more effective representation of the sound propagation as straight or curved rays ("ray-tubes") where the ray separation/density is linked with the sound intensity. (Lamancusa, J. 1993).

Compared to field methods, ray-tracing is lacking the accuracy for low frequency propagation, diffraction and detailed impact of geometric obstacles. Though the ray-tracing approach can be supplemented with added empirical models for sound reflections, propagation into areas behind buildings/screens and noise leaking into refractive "sound shadow" zones. (Poulain, K. 2011)

7.2 Transmission Loss

A way to illustrate the concept of ray-tracing is to follow the computational way from a sound-ray from a source to a receiver by introducing the concept TL, Transmission Loss, which is a measure in dB of the losses in sound intensity level, L_I, along the path due to different physical mechanisms accounted for. The sound intensity level from source to receiver may be written:

$$L_I(x,y) = L_{I,S1m} - TL$$

Where: $L_I(x,y)$ the sound intensity level reached in the ground position at x,y (Note: $L_I = L_p$, sound intensity level equals sound pressure level at standard atmosphere conditions at sea level)

$L_{I,S1m}$ the sound intensity level 1m from the source (at frequency f and the direction of φ, θ)

TL total transmission losses in dB from source to receiver

the individual TL mechanisms/contributions could be categorised as:

TL_{geo}	losses due to the geometrical spreading. In case of a homogenous atmosphere without refraction (constant sound speed all over, no refraction “ray-bending”) the propagation becomes spherical, i.e. radially propagating straight rays, and: $TL_{geo} = TL_{sphere} = 20log(1/r)$, where r = distance from source in meters (gives a reduction of 6dB per doubling of the distance)
TL_{GrRefl}	*TL* due to ground reflection (not an effect along the complete transmission path but a local effect caused by ground reflection, here called “*TL*” anyhow). Yet in SAFTu only one bounce/reflection may be accounted for
TL_{AirAtt}	*TL* due to attenuation in the free air along propagation path between source and receiver
$(TL_{\rho c}$	If computing in sound pressure instead of sound intensity *TL* of sound pressure levels due to a change in air acoustic impedance, ρc, ρ = density of air, c = sound velocity, insignificant for vehicles close to ground. Note: ρc is the conversion factor between intensity and pressure for a plane wave)

(Other TL, or alternately IL (Insertion Loss), mechanisms can be added above, e.g. diffraction into regions behind screens or buildings, which are not accounted for by straight or even refracted rays. Several approximation models exist for these situations.)

7.3 Sound propagation model in SAFTu

The sound propagation is dependent on the medium in which it takes place. In our case with sound propagating in air, properties typically found in weather prognoses (atmosphere profile data, humidity, temperature, wind direction and speed and turbulent kinetic energy) have an impact on TL_{geo} (if accounting for refraction) and TL_{AirAtt} (absorption of acoustic energy).

Though we have some programmed methods accounting for refraction established, allowing estimation of noise reaching “sound shadow zones”, supported by atmospheric profile data, this is not yet implemented in SAFTu. Consequently, currently we assume $TL_{geo} = TL_{sphere}$. The methods capable of managing these matters are prepared partly n previous KTH-CSA projects (U. Tengzelius 2019) and can be implemented/further developed in SAFTu if found needed. An example of application is the modelling of refraction/sound shadow zones which could be applied to find track paths and altitudes depending on wind conditions aiming for “smallest noise footprint”, could be with regard to annoyance or detection.

As of now, terrain obstacles create absolute sound shadows. I.e. no straight rays hitting a natural terrain obstacle like a hill will produce behind it. Meaning that no noise is predicted in corresponding reaching ground grid points behind it. [Note: ground grid points screened by topography in this manner are noted and any simplified diffraction model could be added and implemented to estimate corresponding IL].

Beside (not yet implemented) refraction effects, we do account for the sound speed, and its slight variation with static pressure and temperature, when computing propagation times and resulting noise time-frequency histories in selected ground points.

The sound absorption is slightly dependent on humidity and temperature and but the final result in terms of noise levels on ground will typically vary in the order of ~1 dB if a selection of forecasted “real” atmospheric profile data set or a standard atmospheric data set is applied.

7.4 Noise mapping

The final noise mapping, when noise time histories is computed in ground grid points and contour lines in dB are established, take place in Google Earth where also flight trajectories are displaced. This gridding and noise mapping is outlined in some detail in the SAFTu manual (Tengzelius et al 2025) and in examples given below.

8 Use cases for UAVs - delivery drones

Two use-cases for UAV, delivery drones, have been developed and then analyzed in WP3 using calculation methodologies from WP2 and WP3. The first use-case concerns transport of blood samples etc. between Stockholm Regional Hospitals. A comprehensive pre-study had been performed for this concept in Stockholm region (Region Stockholm, 2023) which gave sufficient information to use as a realistic operational concept case. Results and methodology are presented in a conference article (Orrenius et al., 2024). The second scenario concerns materials transports in Jämtland County that have been developed within the framework of the Green Flyways 2.0 project (Green Flyways, 2022). Resulting noise maps for three different flight routs in the vicinity of Östersund are shown in (Orrenius and Tengzelius 2024).

8.1 Source representations from experimental data

The newly released EASA guidelines for *in-situ* measurement of noise from UAVs up till 600 kg is an important step for realistic assessment of drone noise. The use-case simulated above with different source character at flight and at take-off/landing would not be possible to analyse from lab test data only, e.g. with reference to EN ISO 3744 as required in the EU regulations when assessing sound power of small UAVs (European Commission 2019). The EASA guidelines require measurement at hover and not at take-off and landing which is a limitation. The increased sound generations at take-off, may be estimated from *in-situ* hover data in combination with test bench measurements in which relationships torque-sound power level are determined in combination with assumptions of the vertical acceleration. For the UAV analysed, we have from test bench data that a 10% increase in thrust from the hover thrust level results in about 1 dBA increase in sound power. Such increase in thrust results in realistic vertical acceleration, lifting the UAV to 50 m in 10 seconds. Obviously, a higher climb rate would lead to more starting noise, and it is wise for operators to control the added noise at climb by applying a sensible climb rate. For modelling purposes, in addition to the overall sound levels it will be useful if also spectral data is recorded and presented as described in the newly released ISO/FDIS 5305 (ISO, 2024).

However, it is not judged to be practically reasonable to require directivity data for each type of UAV vehicle for the needs of simulations. For some types of UAVs, directivity patterns can be estimated based on generic directivity models as exemplified in (Orrenius,2024).

8.2 Noise mapping

Noise mapping associated with the UAM for the two use cases developed in WP4 has also been carried out. For the first scenario (Stockholm), the starting point has been a source model with measured noise data (Orrenius et al., 2024). For the latter (Jämtland), source data has been estimated by extrapolating measurement data for a smaller drone with mathematical relationships for drone sources' dependence on rotor design and UAV mass; see reference (Tengzelius, 2025).

The results show, among other things, how the calculation methodology developed in WP2 and WP3 can be used to evaluate noise disturbance concerning flight paths including altitude, location of landing sites, and choice of aircraft and flight mode.

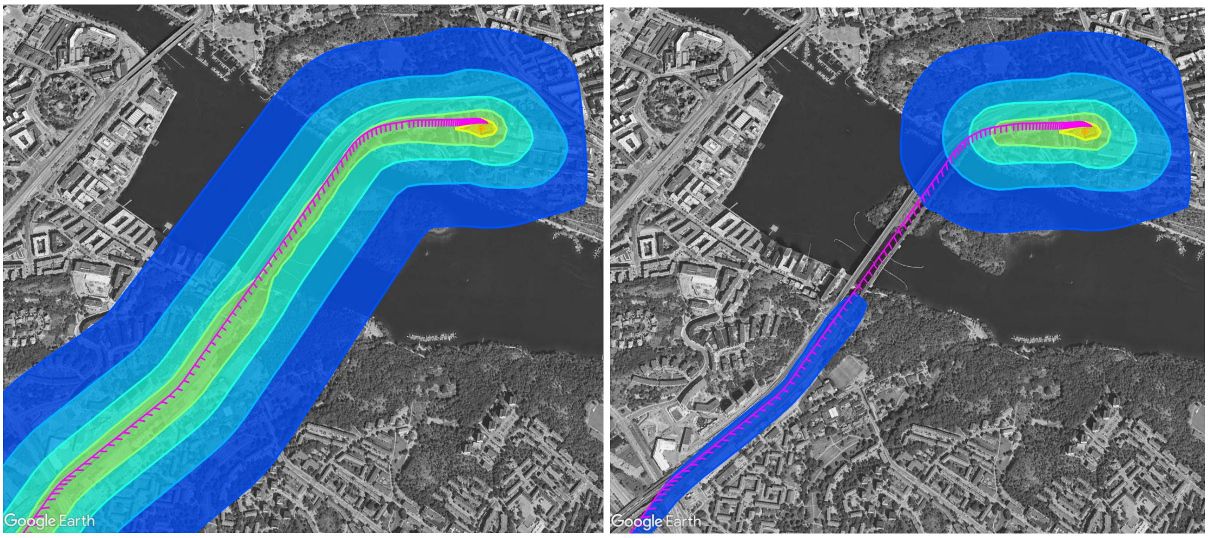

Figure 13. Södersjukhuset landing site noise maps for the quadcopter case (left) and the wing case (right). From reference (Orrenius et al. 2024).

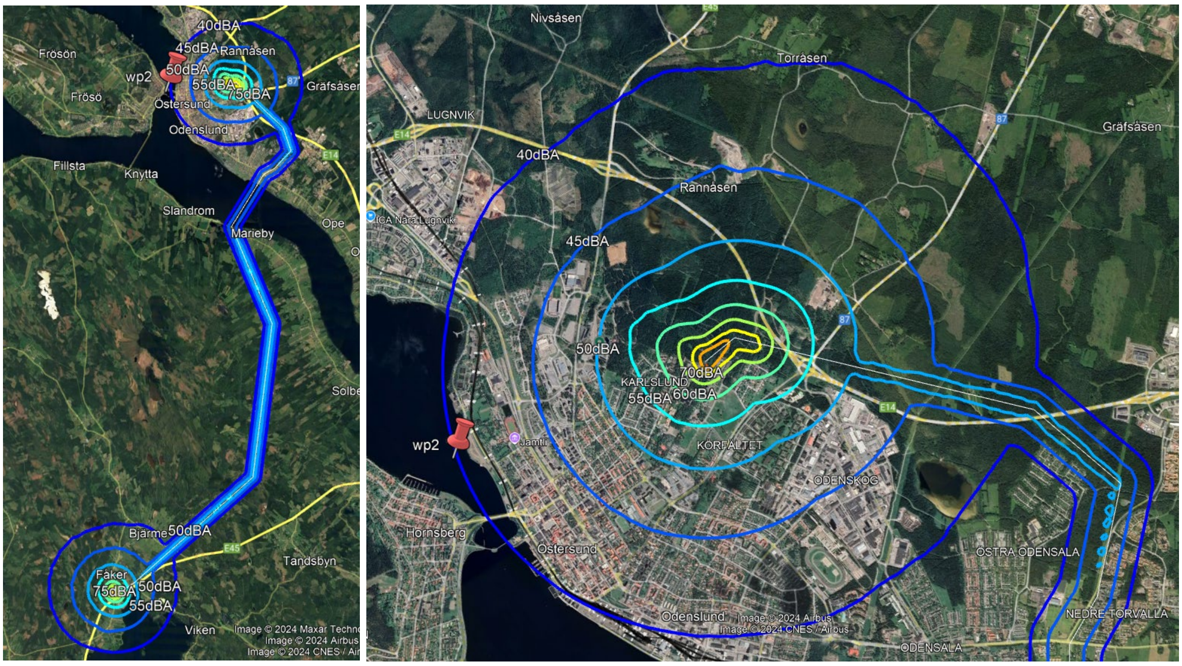

Figure 14. L_{Amax} *noise contours for a flight between Östersund (Solliden) and – Fåker in Jämtland (Orrenius and Tengzelius 2024). Please note that the source data was for this source extrapolated from test data from a smaller drone.*

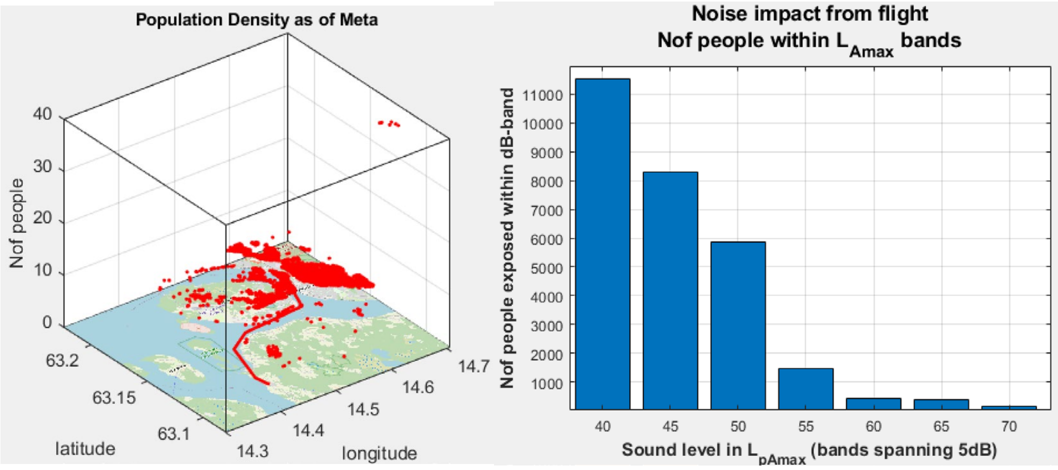

Figure 15. Left: Population density in the vicinity of Östersund city. Right: Number of people within $L_{A,max}$ noise levels bands.

The results show, among other things, how the calculation methodology developed in WP2 (SAFTu) and WP3 (source models) can be used to evaluate noise disturbance concerning flight paths including altitude, location of landing sites, and choice of aircraft and flight mode.

8.3 Benchmark to current Swedish reference values.

The Swedish regulation on Traffic Noise at Residential Buildings (2015:216) contains guideline values for traffic noise. The statutes refer to outdoor values at homes and refer to road, rail and air traffic. The reference values are to be used as guidance in planning and in matters concerning building permits and advance notices, as well as in the examination of permits for airports under the Swedish Environmental Code and regulations issued referring to this code. According to Section 6, noise from airports may not exceed 55 dBA FBN[1] and 70 dBA maximum sound level at the façade of a residential building. Section 7 states that if the maximum noise levels specified in Section 6 are exceeded, the level should not be exceeded more than: (i) sixteen times in the evening between 6:00 a.m. and 10:00 p.m., and (ii) three times at night between 22:00 and 06:00.

On the other hand, the Swedish reference values for industrial noise are stricter, and moreover include a statement that "if the noise spectral contains strong tonal components, the reference levels shall be reduced by 5 dBA". As the spectral contents of multicopter UAVs typically has a high degree of tonal components, it is not unreasonable that a future reference value addressing noise from drones, will be reduced in relation to the present values for airports.

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[1] FBN (Flygbullernivå) is a Swedish energetic yearly average, weighted such that during evenings the noise is rated 5 dBA higher and at night 10 dBA higher. It is very similar to L_{DEN}, but with the evening and nighttime periods starting one hour earlier.

8.4 Conclusions for the use cases studied.

Some key conclusions from the use case studies are:

- Flights using wing mode results in significantly less noise than the same drone using rotor-mode. This has implications for fly-over exposure.
- SAFTu could effectively simulate alternative noise exposure depending of flight path and operational and vertiport placements.
- For UAM scenarios energy based equivalent noise levels can be calculated, but for the cases analysed here the $L_{A,max}$ levels are judged to be of greatest importance regarding acoustic disturbance.
- Air traffic noise regulation: The Swedish reference levels regarding $L_{A,max}$ at building facades will govern compliance rather than L_{DEN} levels (energy summation based).
- Using measured data from a state-of-the-art 20 kg MTOL delivery drone, the present $L_{A,max}$ air traffic reference levels at building facades will be met if the droneport is placed at least 30 m from adjacent buildings.
- The UAM use cases studied allowed comparing choices of flight path and demonstrated how noise simulations can support decisions for acoustics measures at the vertiport and give indications of noise exposure.

Independent of VTOL size, i.e. for delivery vehicles from 1 over 100 kg up to VTOL-taxis (~some tons), we can expect a significantly higher noise emission at take-off and approach/landing when in copter-mode than in level flight/fixed-wing mode. This becomes even more emphasized for vehicles with an increase of sound power when operating close to the ground. Therefore, the location of vertiports can become crucial regarding noise impact, also for smaller delivery drones.

9 Problem formulation and implementation issues

An initial interview study was performed in which central stakeholders gave their views of current and future development of drones including both potential benefits and concerns. In total 10 subjects were interviewed, representing TRV, TS, NV, LFV, Drone networks, Drone regulations, Stockholm region and Stockholm city, researchers in other drone projects (for details see Ulfvengren (2025)). Interviews have been complemented with discussions with our reference group and further by studying webpages and public reports published by Stockholm region, Stockholm city, governmental agencies, authorities, and administrations. Consolidation of this material describes planning processes, organisational dependencies and goals that drives these organisations. For details and full reference list, see Ulfvengren (2025).

This initial part of the study gave an understanding of current activities, roles, perspectives, and challenges for the stakeholders at the receiving end, actors within the municipality. An overall conclusion from these interviews was that the drone concepts discussed were still at an experimental stage. On-going development of regulations and certification of vehicles and operations are currently under development by authorities, mostly at a European level. The focus and challenges concern lack of demonstration opportunities and capabilities for drone developers. A great concern is that the required infrastructure and system for air traffic management need to be provided nationally and locally. LFV has received a governmental assignment to ensure parts of this. But none of this development and ongoing initiatives concern the city's aspects of air traffic, within and over the city in a future UAM.

Drones were not mentioned in any of the reviewed documents on regional planning or in any visions for the city. Further, in interviews and discussions, with stakeholders, several drone concepts were identified, each with different drone vehicle types and sizes and intended services. There is not yet a clear vision of a UAM, consisting of any number and combination of these concepts. This is perhaps not surprising given the early concept stage UAM is in.

However, given the strong push for drone strategies and recent government assignments, on this matter, as well as anticipated challenges for implementation, this report may come timely. It is time to start planning and implementing strategies for UAM. This is especially important since local requirements are not covered or addressed by the regulators or authorities. For example, when the infrastructure is set up, analogous to our road system, the municipality has traffic strategies controlling how many cars can drive on the roads, which streets should be one way or when and where parking is allowed. The municipality is anticipated to strive for similar ownership in deciding the scope of a future UAM.

In addition, a municipalities' focus is its citizens and local businesses, however, they also need to align and contribute to national goals for transportation. For every decision in adapting current ways of working to implementing UAM there will be dilemmas and goal conflicts. A municipalities organisation is complex with different departments, accountabilities and resources. Still governance will be required to implement an UAM.

One objective of APIS has been to provide knowledge, guidance, and recommendations to key stakeholders to facilitate the implementation of future aircraft services, sustainably, regarding noise and disturbances. WP1 had a had a unique focus on the implementation of UAM and a city's sociotechnical aspects of regulations, institutions, infrastructure and current transportation system, planning processes etc. Actors implementing UAM, will be accountable for the results and potential risk for individuals, local businesses and its community. APIS answers far from all these questions but has initiated raising these questions withing the scope of the project. The intention is to maximize drone potential for individuals, businesses, and society, but in a way that minimizes its costs and unintended consequences. As stated, UAM needs to be implemented "properly".

One method for preparing properly in any system development is to develop a concept of operations (CONOPS), including a set of questions that need to be considered and addressed before investing large resources into the system development. This was performed as part of WP1 (Ulfvengren, 2025). For example, what are the current challenges? What value does the new or improved system offer to these challenges? Is it feasible? A scenario analysis can be a first step to understand what needs to be considered for example, when deciding how many drone concepts that should be allowed. What will the effects be in the long run as the market grows? What impact will UAM have on goals set by the municipality for the city, its citizens and businesses? A high-level trade-off analysis was performed as part of the CONOPS in WP1. The objective was to identify complex issues and their interplay in UAM implementation (see below in 9.1.1). The future role for the city in planning for UAM seems to be quite unclear, still, but overall, it will need to handle the challenges to accommodate goal conflicts and manage messy problems (Rittel and Webber, 1973). APIS WP1 developed a conceptual framework summarizing identified issues that will have potential importance on the realisation of future UAM in a city, like Stockholm (Ulfvengren, 2025).

9.1 Complex implementation issues

It is anticipated that the challenge to manage the complexity of implementing UAM includes messy and wicked problems (Rittel and Webber, 1973). When strategic decisions are rare and complex, then problem framing, and problem formulation has been shown to be at least as important as for traditional problem solving. The reason is that there is no optimal solution to these problems (Churchman, 1971). A successful problem formulation that gives a "rich picture" (ibid.) allows externalities, like noise, to be factored in already in design to avoid surprises with undesired and unintended consequences.

One problem formulation in this study focused on the uncertainty of noise issues regarding an UAM. It was framed to relate to innovation capabilities in Stockholm city and the sociotechnical system aspects of implementing UAM. The problem formulation was also inspired from earlier research projects and known experiences from aviation noise issues, including non-acoustical issues in aviation as well as best practices in participative innovation and methods for managing wicked issues in complex societal issues. For example, noise exposure and annoyance as well as potential impact on well-being and health need to be balanced with goals benefitting or contributing to climate or transportation goals. Innovation issues with an on-going concept and experimental driven innovation may be very challenging to govern. In research on "experimental governance" (Eneqvist, 2022) describes examples of bottom-up driven experimental concepts that clashed with top-down goal-driven processes. This frame was chosen mainly because of the anticipated challenges drone implementation may have for societal acceptance. Another perspective was to problematize the rationale behind drone strategies at EU and national level with respect to its potential to contribute to resolving issues of urbanization such as mobility and climate and transport goals.

9.1.1 Trade-off analysis in relation to UAM implementation

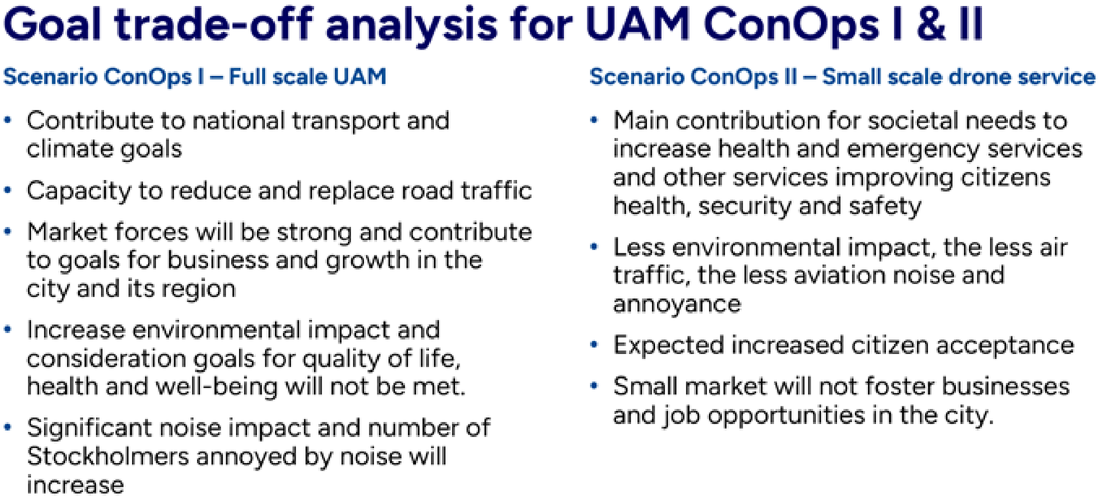
A task in WP1 was to develop a concept of operation, CONOPS, see WP1 report (Ulfvengren, 2025). A part of this process is to analyse alternatives and to perform scenario trade-off analyses. The scenarios were developed to reason around the effect of combining various drone concepts within and over a city. Two scenarios for UAM implementation at different scales were analysed with respect to trade-offs between goal achievements and conditions for innovation within a city, including its citizens. Both scenarios have advantages and disadvantages. This complex interplay is described in the conceptual framework for the implementation of UAM (Ulfvengren, 2025).

The two scenarios selected was a small-scale UAM (small drones for emergency services and health care) which were mostly mentioned as feasible in the interviews and a full-scale UAM (services for delivery and passengers transport) which were mostly mentioned in policy documents and government assignments. The scenarios were compared with respect to trade-offs in relation to goals for transport and environment and trade-offs between various conditions for innovation.

In both scenarios benefits and challenges were identified with respect to national and local goals for transport and environment as well as for conditions for innovation and integration into current transport and innovation system. The goal trade-off analysis (table 1) is based on for example UAM potentials as described in EU's drone strategy, national and local goals for transport and environmental goals for citizens. The innovation trade-off analysis (table 2) is based on current practice and recommendations for innovation in Stockholm, acceptance studies, previous studies of aviation noise as a wicked issue (Ulfvengren, 2023) and previous studies of integrating waterways and boat traffic into the public transport in Stockholm (Ulfvengren et al., 2020).

The scale of an UAM will have implications for conditions for both innovation as well as goal achievements and costs. Further this depends on how a UAM is implemented. Conditions for innovation will depend on the level of acceptance, the level of noise exposure and annoyance, benefits for individuals, businesses and society, alignment with current planning processes etc. Goal trade-offs need to be considered with respect of the innovation trade-offs. A full-scale UAM has both benefits and disadvantages for innovation and goal achievements, but it is not clear how to optimize to maximize UAM benefits while minimizing its costs.

Table 1. Comparison of trade-offs in goals for a full-scale and small-scale UAM (Ulfvengren et al., 2024)



Goal trade-off analysis for UAM ConOps I & II

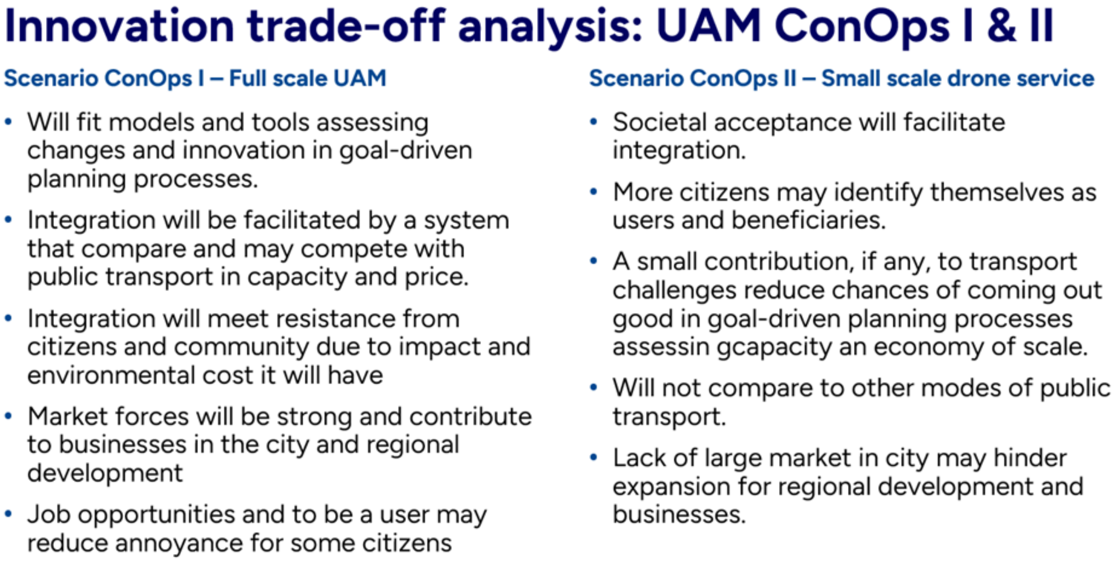
Scenario ConOps I – Full scale UAM

- Contribute to national transport and climate goals
- Capacity to reduce and replace road traffic
- Market forces will be strong and contribute to goals for business and growth in the city and its region
- Increase environmental impact and consideration goals for quality of life, health and well-being will not be met.
- Significant noise impact and number of Stockholmers annoyed by noise will increase

Scenario ConOps II – Small scale drone service

- Main contribution for societal needs to increase health and emergency services and other services improving citizens health, security and safety
- Less environmental impact, the less air traffic, the less aviation noise and annoyance
- Expected increased citizen acceptance
- Small market will not foster businesses and job opportunities in the city.

Table 2. Comparison of trade-offs in innovation conditions for a full-scale and small-scale UAM (Ulfvengren et al., 2024)



Innovation trade-off analysis: UAM ConOps I & II

Scenario ConOps I – Full scale UAM

- Will fit models and tools assessing changes and innovation in goal-driven planning processes.
- Integration will be facilitated by a system that compare and may compete with public transport in capacity and price.
- Integration will meet resistance from citizens and community due to impact and environmental cost it will have
- Market forces will be strong and contribute to businesses in the city and regional development
- Job opportunities and to be a user may reduce annoyance for some citizens

Scenario ConOps II – Small scale drone service

- Societal acceptance will facilitate integration.
- More citizens may identify themselves as users and beneficiaries.
- A small contribution, if any, to transport challenges reduce chances of coming out good in goal-driven planning processes assessin gcapacity an economy of scale.
- Will not compare to other modes of public transport.
- Lack of large market in city may hinder expansion for regional development and businesses.

10 Mitigation of drone noise

10.1 Drone design and operation

The use cases described in Chapter 8 illustrate how both operational choices and the choice of UAV type for a certain flight route can greatly affect the noise exposure of the people living in the vicinity of the flight route and in particular the start and landing places. This means that the choices made in the set-up of a local UAM, concerning UAV system to be used, and the associated routing, can greatly contribute to the chances of success for future UAMs. To proactively manage noise exposure by low noise design of vehicles and their operations has the potential to remove negative connotations due to perceived annoyance for a particular drone type, but also for a particular drone service operating with a "noisy" drone.

From the analysis of the use case simulation results as well as the source models derived from supplier test data and from the literature, several different measures to reduce noise can be identified.

10.1.1 Low noise UAVs

Substantial efforts to reduce UAV noise are made by research institutes and manufacturers by measures on noise the source. Based on that the main source is associated with the rotors and the airflow created by these as discussed in Section 6.1, control measures include rotor housing in short ducts, optimized rotor blades and positioning as well as noise reducing rotor lay-outs including increased rotor diameter and optimized pitch. A very effective noise reducing measure is the introduction of wings to replace the need or lift from the rotors. See the benchmarking simulation results as presented in Figure 13 and Figure 14. Clearly wings also adds to the range of the UAS but comes with additional weight and complexities in the design and operation in relation to multicopter UAVs.

For operators planning the introduction of UAM, noise can be addressed both in specifying noise levels when buying the UAVs to be flown, or in a technical specification for the service provider in the case that the UAM service is outsourced to another party. A starting point for setting acoustic requirements when deciding on the UAV to use may be the EASA guidelines (EASA, 2022) for measuring flyover and hover noise.

10.1.2 SAFTu for route planning and location of drone ports

As illustrated by the noise maps for the use/cases presented in Chapter 8, most noise exposure is typically adjacent to the landing sites. Fly over drones can also be perceived as annoying, for example for multicopters with high sound power, forced to fly at low altitude in a regulated area in the vicinity of an airport. However, the location of landing sites is likely to be the main noise concern, at least for small scale UAM implementation with a limited number of UAV flights.

Regarding route planning, similar considerations for noise exposure should be made as when new roads or rail roads are being planned. An added challenge for UAM is the fact that overhead sources are typically viewed as more disturbing than ground borne sources. In addition, it is generally not possible to control the exposure by means of noise barriers and it may also be more challenging to design noise sheltered areas, e.g. behind a building.

Regarding placement of drone ports, a handbook is available from Swedavia (Ehk and Åberg, 2023) and requirements for vertiports at larger scale has been identified (Salehi and Wang, 2021). SAFTu noise simulations bring value for several decisions required of drone port location (Ehk and Åberg, 2023; Salehi and Wang, 2021) and flight routes towards the drone-port. The results from such simulations can support decision-making and be used for communication of the expected noise exposure. Moreover, it is generally wise to involve affected citizens early on, to explain the benefits of the new transportation mode, the measures that have been taken to mitigate noise: use of silent UAVs and the optimization of flight routes, and measures on the infrastructure for example improved windows in facades. See further Chapter 11 below with recommendations.0

10.2 Implementation strategies to mitigate noise annoyance

One identified complex issue concerning implementation of UAM are non-acoustic aspects (Porter et al., 2021) such as emotions, anger, control, fear, justice, and trust. Strategies mitigating that non-acoustic effects contribute to annoyance could be to apply best practice form participative innovation (Region Stockholm, 2019) and methods for managing wicked issues (complex societal issues) (Jordan et al., 2010).

In addition, tools that may be used in communication and training align well with participative approaches. The noise simulation capability of SAFTu has great potential also to mitigate noise non-acoustic aspects. Tools like SAFTu has been verified in the project to be useful by different stakeholders, both developers, operators, decision makers and regulators to perform simulations of noise and routes. SAFTu can also be used in education, communication, evaluation, noise forecasting, decision support.

Tools for monitoring acceptance and attitudes towards drones for users, as well as non-users, should be in place before operationalizing UAM of any kind. Simulations and modelling should be complemented with methods to assess effects on well-being and health. (Ulfvengren, 2025)

10.3 General aspects related to UAM implementation

Noise levels, annoyance and acceptance are all aspects that will benefit from choices made for vehicle design and operations especially as a complex network of drones may grow exponentially (FAA, 2020). Further simulations of UAM will be required to assess system dynamics implications in the long run. The critical message is that each decision leading up to strategies, regulations and processes for a municipality preparing for implementation of UAM will determine the conditions for the future. Annoyance and acceptance will not only depend on sound exposure but also on non-acoustical factors embedded in for example, citizens' participation in implementation or trust in that regulation compliance is consistent. To recover from a breach of trust will come at high cost in acceptance among citizens. There needs to be a plan to manage feedback and complaints from the start. Finally, there needs to be a change capability present to act on relevant input and adjust.

Beyond the analysis in this project is how cities will gain sufficient control and ownership of the development of UAM and traffic volumes in the airspace above the city. This topic has not been studied in detail in this project but enough to state that close collaboration among authorities controlling and regulating air space is recommended. The Swedish transport authority mention this with emphasis in their own report (Transportstyrelsen, 2024).

11 Recommendations

Some key recommendations for different stakeholder groups as derived from the APIS project results are given below.

Drone developers and operators:

- Search for methodology both on the UAV source and on the operational procedures to limit noise exposure from products
- Engage in working groups for standardized measurement schemes and certification
- Address noise questions early in the discussion of UAM implementation
- Apply simulations to assess the noise exposure prior to finalizing location of drone ports, flight routs and choice of drone type

Municipalities and regions:

- properly plan for a UAM implementation in current organization for traffic, noise, innovation, citizen dialogue
- collaborate within the city and the region as well as with authorities and regulators to gain sufficient ownership of drones within and over the city
- simulate quantity and type of UAM traffic including number of movements, and vehicles, considering long-term growth
- develop knowledge and raise awareness of the complex relationships in UAM implementation (noise, annoyance non-acoustical aspects and societal acceptance)

Authorities and regulators:

- Provide consequent regulations and guidelines for drone operations, based on safety and noise exposure.
- Establish relevant metrics and limit values for drone noise, which preferably includes perceived annoyance assessments
- Further research is needed to address the nose exposure from relevant UAM scenarios and the associated annoyance for citizens

12 Future research

Through the review of the literature and the APIS project results, three main fields of future research are identified:

A. *Improved modelling capacity of UAV noise.* This topic includes (i) improved modelling of UAV sources, particularly those types which have several propulsion systems and associated flight modes; (ii) synthesis of calculated UAV noise with that from existing sources like trains cars and conventional aircraft and (iii) modelling of noise propagation in urban environment in which reflections and diffraction of sound at buildings etc, strongly influence the propagation.

   All three of these areas of research should be addressed, and new methodology need to be developed, or existing methodology extended/improved, to assess disturbance from future UAM. For example, assessing the increased noise annoyance and associated epidemiological risk factors, when a limited number of daily UAV flights adds to the noise from traffic in a city requires (i) methodology for adequate and realistic UAV source models based on operational data, (ii) synthesis with traffic noise as well as (iii) capacity to analyse screening from buildings to assess how todays "silent zones", for example court yards, will be affected when UAM becomes a more pronounced part of city soundscapes. In the long term, to address large scale implementation according to Section **Error! Reference source not found.**, methodology should be able to answer questions arising regarding noise exposure if a significant part of the noisy transports in a logistics application area is shifted to UAM.

B. *UAM implementation and noise regulation:* To address future regulations regarding noise limits and recommendations to stakeholders related to implementation of UAM including the planning of networks of landing sites, there is a need to analyze different types of scenarios with respect to flight paths and frequency. When it comes to regulation of UAM noise, the capacity to understand combined effects of drone noise with that from existing sources (synthesis), as well as the concept of "silent zones", as discussed above, are essential. Another area for investigation is to assess potential effects on health and well-being by estimating how traffic volumes will add to environmental noise and estimate a threshold when UAM worsens the situation on average. For this a traffic model is being developed in which "what-if" scenarios can be tested with varied traffic types and volumes. This model and developed methodology will be developed together with Stockholm's traffic and environmental departments to include requirements for traffic strategy and environmental consequence analysis as part of the implementation of UAM in Stockholm.

C. *Annoyance from UAV traffic:* A solid understanding of the perception of UAV noise is critical for effective and relevant regulation and guidelines regarding future drone operation and implementation of UAM. Better understanding of the perceived annoyance with respect to different UAV types and associated source mechanisms as discussed in Section 6.1 is required. In this context, non-acoustical effects like the perception bias associated with the (perceived) UAM application, as briefly introduced in Section 10.3, also need to be understood better.

Based on identified research needs as above, two continuation projects are planned: BUS (Bullerkonsekvensbedömning för UAM implementering i Stockholm) and TYSTARE addressing integration of drone noise with existing methodology for assessing traffic noise as well as acoustic effects from screening and reflection by buildings. Also refined source models are addressed.

13 Concluding remarks

From the sound levels calculated in the two use-case scenarios analysed, we may conclude that operation of fixed wing delivery UAVs, will not significantly add to noise levels in the city. Fixed wing delivery UAVs are generally relatively silent and will hardly be noticeable in relation to general city noise. In addition, the speed of the fixed wing UAVs is fairly high, such that the overhead disturbance will pass in a few seconds. On the other hand, the corresponding multicopter UAVs are substantially noisier simply because of the need for lifting the entire UAV mass during flight.

Based on the results from the Region Stockholm UAM use-case, using noise data from a state-of-the-art 20 kg MTOL, one conclusion is that the Swedish air traffic reference levels (Naturvårdsverket, 2024) regarding $L_{A,max}$ measured at building façades close to a new droneport installation will govern the compliance with the noise exposure regulation rather than L_{DEN} levels (energy summation based). For the case analysed with a uniform distribution of movements over the 24 hour cycle, the number of landings at a hospital droneport must exceed 70 per day for the L_{DEN} reference levels to be exceeded assuming the $L_{A,max}$ levels is at the reference level 70 dBA. The same holds true if the noise from a new droneport is assessed with respect to the Swedish reference levels for Industrial noise (Naturvårdsverket, 2024).

From simulations using measured source data from a state-of-the-art 20 kg MTOL delivery drone, it is found that the present Swedish $L_{A,max}$ air traffic target levels, stipulated at building façades, will not be exceeded if the droneport is located at least ca 30 m from adjacent buildings. However, in view of the highly tonal character of drone noise, it is not unlikely that future reference values may be lowered in relation to those from regular aircraft, to reflect the greater annoyance perceived by exposure to noise from drones (EASA 2021, Schäfer et al. 2021, Lottinga et al. 2023), and also because a new kind of air-borne noise source may be experienced as intrusive, especially in environments previously unaffected by aircraft noise (EASA 2021).

Simulations are widely recognized for their role in supporting well-informed decision-making. By visualization of flight routes and by graphical and aural presentation of noise impact in different scenarios, simulation tools can effectively support the planning of suitable routes and the location of droneports that will mitigate unintended and undesired consequences and increase societal acceptance of drones. Furthermore, calculation results can be integrated into various actors' processes for regulations, urban planning, traffic planning and not the least important, communication with affected citizens. In addition to noise maps, simulation results from SAFTu can be postprocessed in modern tools such as virtual reality and, if combined with sound recordings, auralization tools, to provide effective ways to inform and engage the public.

Finally, we conclude that decisions regarding drone integration made without adequate information may result in systems with unforeseen and undesirable consequences, particularly when these systems rapidly scale over time. The European Green Deal **Error! Reference source not found.** includes a criterion that no people or places should be left out. This includes those residents who will be affected by the construction of new droneport infrastructure in their immediate area and noise from the associated traffic.

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