Analysis of noise optimal approach procedures with on-site statistical meteorological effects

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This study uses a design space exploration methodology to investigate the potential noise reduction benefits from optimized precision approach procedures. Different procedure designs are generated by varying the turn radii of the procedure's curved segments and each design is evaluated based on its noise impact on the population. Using an existing procedure at Arlanda airport in Stockholm, it is demonstrated that by varying the horizontal procedure design with essentially no impact on fuel burn and emissions, the noise-affected population is reduced by approximately 5000 individuals, under standard atmospheric conditions. When local meteorological data are included, this reduction is significantly diminished to less than 350. The selected conditions lead to an increase in the noise-affected area, reducing the benefits of the noise optimal procedure. The findings highlight the importance of incorporating meteorological conditions in procedure design to perform a realistic assessment of the noise impact on the population.

1 Introduction

Performance-Based Navigation (PBN) procedures are being increasingly adopted in global aviation resulting in improved flexibility in flight procedure design and in greater operational efficiency. Among these procedures is the RNP AR (Required Navigation Performance Authorization Required), which requires the aircraft to be equipped with high precision on-board equipment, but results in increased safety and flexibility [1], [2]. Although these procedures already demonstrate improved efficiency, optimizing them for specific airports and conditions may represent one of the most effective strategies for reducing the environmental impact of existing aircraft.

Previous studies related to RNP AR procedure design have explored various optimization techniques to improve efficiency and minimize negative impacts. Hasegawa et al. [3] presented a method for optimizing RNP AR approach procedures for minimum fuel consumption. The optimization parameters included waypoint positions and speeds, and a genetic algorithm was used to minimize the fuel consumption while accounting for procedure design constraints. Morscheck [4] focused on minimizing the number of people affected by noise from approaching aircraft alongside limiting the consumed fuel. The optimization was performed by varying a set of straight and curved segments that constructed the procedure, while also allowing for variation in the number of segments. It was demonstrated that increasing the number of segments allows for increased flexibility and results in greater improvement. In order to save calculation time, simplified methods with pre-calculations were used for the fuel consumption and noise predictions and a populated area of $200m$ x

$200m$ was matched to each trajectory point and used for the population calculation. Finally, Cho et al. [5] proposed a design tool with trade-space exploration in order to investigate the trade-offs between several conflicting variables. The procedures were constructed using a grid of waypoints connected in multiple directions covering a large range of headings and approach paths. The fuel consumption, emissions and flight time were calculated using a surrogate model and the noise impact was estimated using the Integrated Noise Model [6] based on standard atmospheric conditions.

In the present study, a design space exploration analysis is presented. The procedures are defined through a series of waypoints and straight or curved segments and different designs are generated by varying the turn radii of the curved segments. Contrary to the studies performed by Morscheck [4] and Cho et al. [5], detailed calculation of the noise impact is performed, by implementing a component-based noise prediction model to evaluate the noise impact on the population. An advantage of this model is that it allows for real-time computations something that pre-calculations cannot do. Additionally, it enables the inclusion of the wind effect which is not possible with the models presented in [4] and [5]. The impact of noise on the population is assessed using a population grid for the entire area, which, although more time-consuming, provides a more realistic representation of the noise impact than the $200m$ x $200m$ inhabited area used in [4]. As a case study, an existing RNP AR approach procedure at Arlanda airport in Stockholm is optimized and statistical meteorological data from the area are used to investigate the noise impact of the optimal procedure in different conditions.

The rest of the paper is structured as follows: In Section 2 the methods and tools that were used to perform the present study are presented. These include the simulation framework, the procedure design process and the design space exploration methodology. In Section 3, results for the selected case study are presented, starting with the design space and the noise optimal procedure and followed with an extensive analysis of that procedure under statistical weather conditions from the procedure location. Finally, in Section 4 key outcomes are summerized and discussed.

2 Methods

2.1 *Framework for aircraft multidisciplinary analysis*

For the purpose of the study, several simulation tools are combined into a framework that allows for multidisciplinary design and optimization of aircraft systems. The framework, which has been used in several studies in the past [7], [8], incorporates a procedure design module, an aircraft and engine performance module, coupled with engine conceptual design, an emissions estimation module and a noise prediction module. All modules are based on Chalmers developed tools and are coupled together with an open-source high-performance computing platform for systems analysis, namely OpenMDAO [9]. The calculation process starts with the procedure design and flight performance model which feeds data into the in-house engine performance code, GESTPAN [10], followed by the weight and dimensions estimation tool, WEICO [11]. NO_x emissions are calculated based on a semi-empirical model from AECMA (European Association of Aerospace Industries), implemented in the emission code CHEESE as described in [7]. A system-level noise analysis is then performed using the open-source noise prediction tool, CHOICE [12], [13] and the noise-affected population is estimated by interpolating the population grid derived from EU GHSL - Global Human Settlement Layer data [14] as described in [15]. For the case where the meteorological data are applied, these are included in both the performance of the aircraft and the noise propagation. For the former, the same ground path is kept as for the no wind case, and the aircraft heading, speed, and bank are calculated to follow the desired flight path. For the latter, a ray tracing methodology is used where the sound ray trajectories are calculated by solving the ray-tracing equations which include the ray path and the wave-slowness vector as presented by Pierce [16].

2.2 *Procedure design and aircraft performance*

The procedure design can be simplified by decoupling the horizontal and vertical aircraft motion. The design process begins from the definition of the lateral profile which for an RNP AR procedure can be constructed through a series of waypoints which are connected with either straight or curved segments with a specified turn radius. The coordinates of the waypoints and the turn radius for the curved segments are therefore all that is required to define the horizontal path. Within a straight segment the aircraft track angle remains constant whereas in a curved segment, the change in track angle can be calculated as

$$\Delta\psi = \frac{ds}{2\pi R} \tag{1}$$

where ψ is the heading or yaw angle, ds is a small distance increment and R is the turn radius. In the above equation, standard atmospheric conditions with no wind are assumed and, hence, the heading and track angle coincide.

With the horizontal path defined, the vertical profile can be built by defining the speed and altitude of the aircraft when passing above each selected waypoint and the aircraft performance can then be estimated following the system of differential equations that describe the motion of the aircraft.

$$\begin{cases} \dot{V} = \frac{1}{m}\left(T\cos\left(\alpha\right) - D - W\sin\left(\gamma\right)\right) \\ \dot{\psi} = \frac{1}{mV\cos\left(\gamma\right)}\left(T\sin\left(\alpha\right) + L\right)\sin\left(\phi\right) \\ \dot{\gamma} = \frac{1}{mV}\left(\left(T\sin\left(\alpha\right) + L\right)\cos\left(\phi\right) - W\cos\left(\gamma\right)\right) \\ \dot{x} = V\cos\left(\gamma\right)\cos\left(\psi\right) \\ \dot{y} = V\cos\left(\gamma\right)\sin\left(\psi\right) \\ \dot{h} = V\sin\left(\gamma\right) \\ \dot{W} = -f \end{cases} \tag{2}$$

where T is the thrust for the total number of engines, α the angle of attack, D the drag, L the lift, ψ the heading or yaw angle, h the altitude, and f the fuel consumption. To solve the system, an additional parameter is required, namely the lift-to-drag ratio which is assumed to be configuration dependent. For the A321neo aircraft type, used in this study, the configurations and lift-to-drag ratio are presented in Table 1.

This system of equations applies to the no-wind case and some adjustments need to be made to account for the effect of the wind. The derivation of the modified system can be found in [17]. In this study, the intention is to keep the flight path unchanged under all

Table 1: A321neo approach configuration settings and lift-to-drag ratio [17].

Configuration	Slats (^{o})	Flaps (^{o})	Landing gear	L/D
Clean	0	0	Up	17.76
1	18	0	Up	15.38
2	22	14	Up	12.45
			Down	9.35
3	22	21	Down	8.88
FULL	27	34	Down	8.32

conditions and therefore, in the presence of wind, the heading angle, true airspeed vector and bank angle must be adapted to result in the desired course and vertical path.

In the present study, the focus is on approach procedures and, hence, the vertical flight path is restricted to level flight and descending segments. For passenger comfort reasons, a lower limit of $-4.5°$ is set for the descent angle, while a bank angle limit of $25°$ is applied as suggested by the regulations [18]. In general, only constant speed and decelerating segments are considered but under certain wind conditions the aircraft might need to accelerate. Finally, as only a small flight segment is considered where the engine is running at relatively low power, the change in weight due to the consumed fuel can be neglected and the last term in eq. (2) can be removed.

2.3 *Design space exploration*

Predefined RNP AR procedures already exist in most airports where such operations are permitted. The purpose of the design space exploration tool is to assess whether these existing designs can be further optimized. In the present study, the focus is primarily on reducing the noise-affected population, while fuel consumption and NO_x emission are computed to ensure that there are no adverse effects.

OpenMDAO was employed to perform a design space exploration focused on the horizontal flight path. The initial procedure design, presented in Figure 1, was based on the RNP y RWY 01R (AR) which is an RNP AR approach procedure that is regularly used at Arlanda airport. The procedure definition can be found in Sweden's Civil Aviation Administration, LFV, website [19].

Throughout the design space exploration, the point of entry to the procedure, AXWAL, was kept constant and so was the final segment from SA638 until the landing runway, RW01R. The selected design variables were the turn radii of the two turns included in the procedure, with an allowed variation between -2.5 NM and 2.5 NM for each turn. This resulted in a lateral relocation of the waypoints, between AXWAL and SA638. The initial altitude and speed were also kept constant, while the vertical profile was adjusted to each new design, by keeping the same altitude and speed values above each waypoint. The extension of landing gear and high lift devices was controlled by altitude or speed limits.

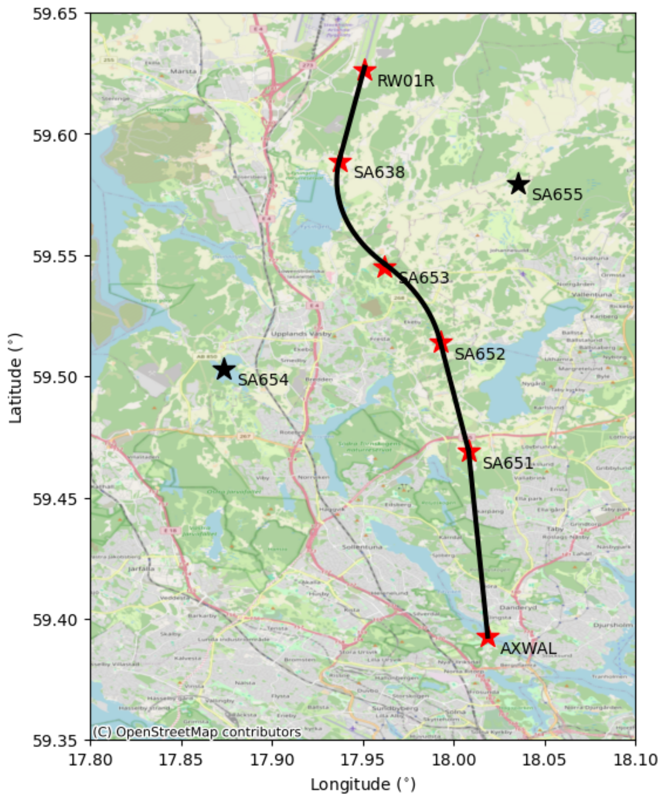


Figure 1: RNP y RWY 01R (AR) (Reproduced from [19]).

3 Results

3.1 *Design space*

The resulting search space is presented in Figure 2. The horizontal axis indicates the variation in turn radius for the first turn, i.e. the southernmost turn, and the vertical axis for the second turn. The contour levels represent the amount of population experiencing sound exposure level above 65 $dB(A)$. The original procedure design is located on the $(0,\ 0)$ point where the two dashed lines meet and corresponds to a population of 66318, while the minimum is found where the magenta circle is located, $(2.13,\ -1.79)$, and corresponds to an affected population of 61271. The white spaces suggest that the design generated by the specified turn radii was discarded either because the descent angle or bank angle limit was exceeded or because it was not possible to design the procedure by keeping the entry point constant.

The two procedures and the affected population distribution are shown in Figure 3. As can be seen, in the modified RNP the aircraft first performs a wide turn followed by a narrower turn before aligning with the runway. This results in a shift of the noise footprint towards the north east and consequently to a reduction of the noise impact for

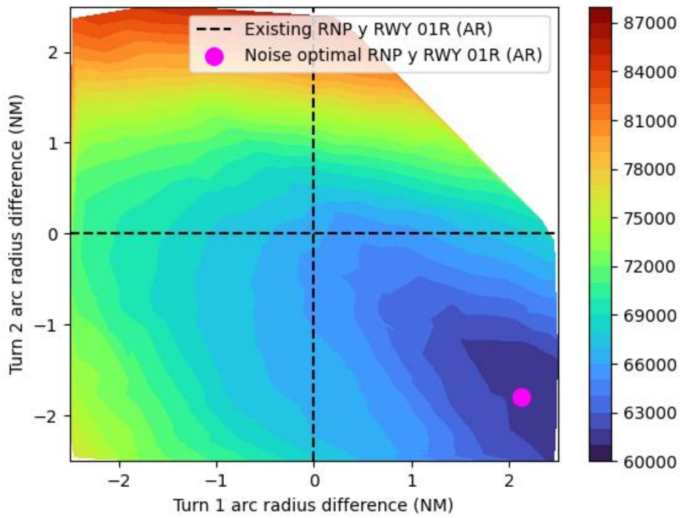


Figure 2: Noise-affected population relative to turn radius variation for standard atmospheric conditions.

some residents in the more densely populated area located in the west side. In terms of emissions, the two procedures are very similar with a total fuel and NO_x mass of 56.4 kg and 615 kg, respectively, for the existing procedure and 56.0 kg and 607 kg for the optimal procedure.

3.2 *Noise optimal procedure analysis*

The design space exploration that was performed in the previous section shows that although the original procedure already demonstrates good results in terms of noise-affected population, further improvement could be achieved with small adjustment of the original design. However, this evaluation was performed assuming a standard atmosphere and ISA conditions. For completeness, it is important to evaluate the two procedures under weather conditions which are representative of the procedure location. For this purpose, historical meteorological data from the procedure location were used which were collected over a 10-year period from 2009 to 2018. The 95th percentile wind speed was calculated for various wind directions with a 10° interval [20]. The data selection process began by filtering out the wind speeds that would result in a tailwind component of more than 5 kt for the selected runway, causing the aircraft to land on an alternate runway. From the down-selected data, the maximum 95th percentile wind speed was chosen and only a variation with altitude was assumed. For the temperature, the 95th percentile value of all years was used. The selected data resulted in a temperature of 20.9 $°C$ at mean sea level and a wind speed of 18.7 kt from north to northwest (wind direction of 350°) at a height of 35 m above the ground.

The resulting sound exposure contours are presented in Figure 4. In both cases, the effect of the wind is evident as the contour maps indicate a higher spreading towards the south. In this case, the number of people affected by the existing RNP is 150082 while for the optimal procedure the affected population decreases to 149754. These numbers are

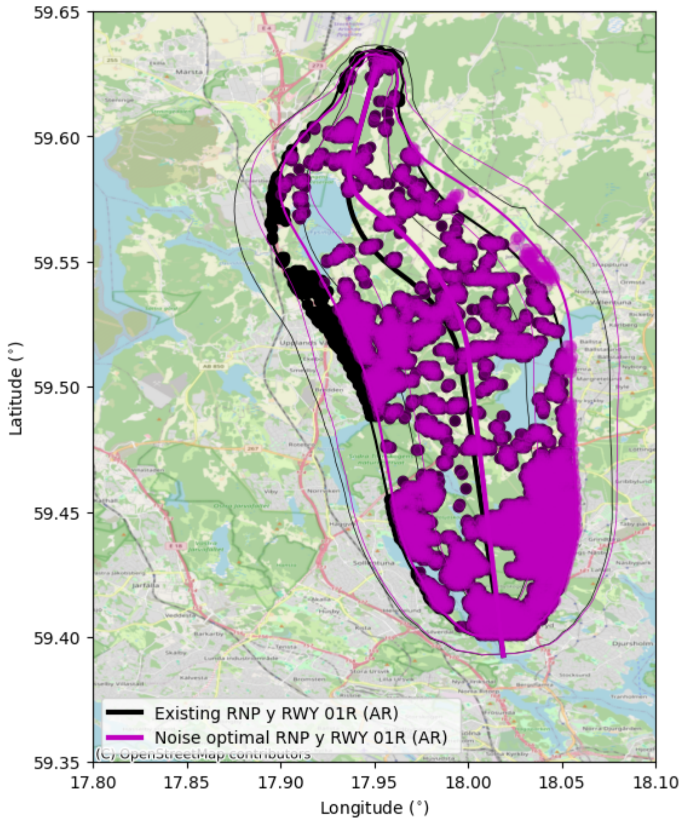
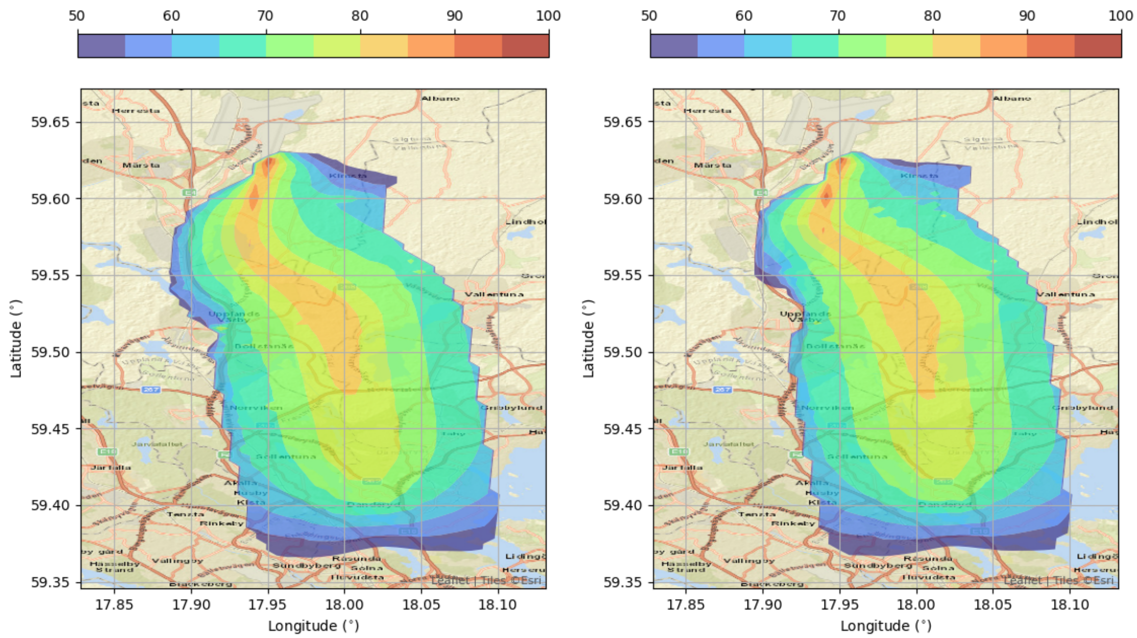


Figure 3: Noise-affected population distribution for the existing and optimal procedure.

significantly increased compared to those presented in Section 3.1. This is mainly attributed to the temperature difference, as for the selected conditions the atmospheric temperature is 5.9 $^{\circ}C$ higher compared to the ISA temperature used for the results in the previous section, leading to lower atmospheric absorption and therefore increased noise level on the ground. If, for example, only the temperature would be accounted for, i.e. zero wind and propagation without consideration of wind and temperature gradients, the affected population for the existing and the optimal procedure would equal 122711 and 118250, respectively. The remaining difference in noise-affected population can be attributed to the effect of the wind as well as differences in performance characteristics.

Some key performance data of the noise optimal procedure in ISA and statistical conditions are presented in Figure 5. As mentioned in Section 2.1, and as is evident from the figure, the path and true airspeed of the procedure are kept constant under all conditions. This results in higher power requirement when the statistical data are used due to the strong headwind. This increased thrust level results in a higher noise level emitted by the aircraft.

From Figure 4, it can be observed that the modified RNP results in the displacement



(a) Existing RNP procedure.

(b) Optimal RNP procedure.

Figure 4: SEL contours for the existing and optimal procedure in real weather conditions.

of the noise-affected area towards the northeast which is less densely populated. However, the shape and areas of the different noise levels have also been modified indicating that the noise level in certain areas, especially those located in the inner side of the steep turn, might have increased. A detailed analysis of the noise-affected population for the different noise levels and conditions is presented in Table 2. In the same table, the total consumed fuel and NO_x mass can also be seen. Interestingly, under the statistical weather conditions, the noise from the optimal procedure seems to affect fewer people in all cases apart from the 75 $dB(A)$ level, while under ISA conditions more people are affected from the 75 $dB(A)$ and 80 $dB(A)$ level, compared to the existing procedure. In terms of emissions, the two procedures are very similar, indicating that improved noise impact can be achieved without sacrificing emissions. The higher emissions observed under the statistical conditions can be partly attributed to the higher atmospheric temperature as well as to the increased power requirement, as seen in Figure 5. Furthermore, due to the the lower ground speed, the flight time is increased by about 80 seconds, resulting in a further increase in emissions.

It becomes evident that it is important to consider local weather conditions when procedures are designed as the impact of each procedure might vary depending on the conditions. This analysis should perhaps be complemented with the impact that each noise level would have on human health in order to draw more concrete conclusions as to which procedure would be more beneficial.

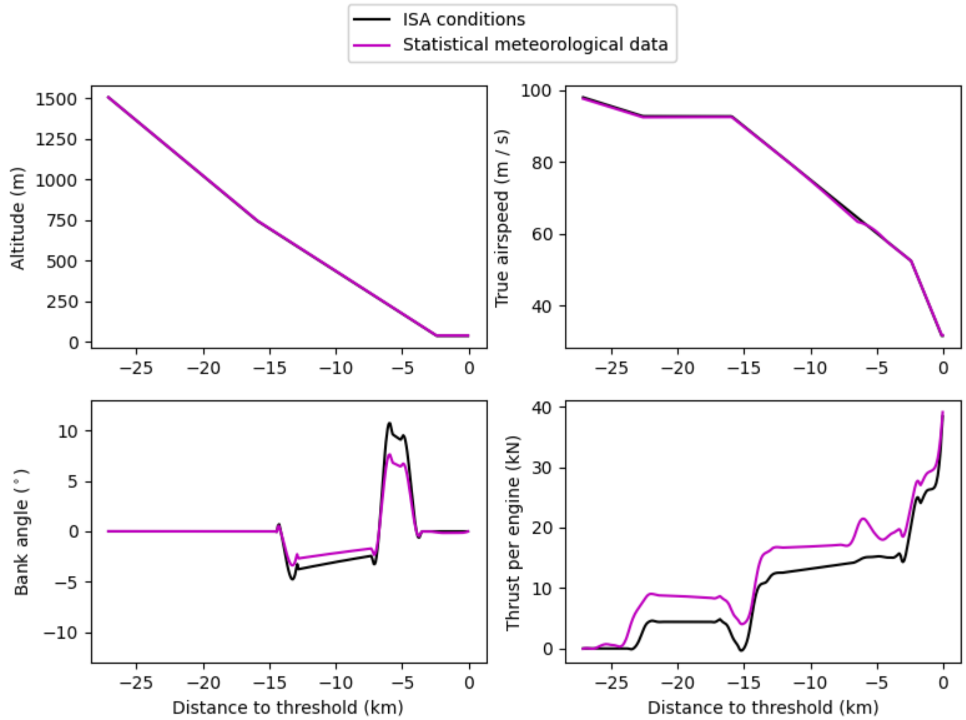


Figure 5: Performance characteristics for the noise optimal procedure in standard and statistical conditions.

Table 2: Noise-affected population at different noise levels and total emissions.

	Statistical weather conditions		ISA weather conditions	
SEL (dB(A))	Existing	Optimal	Existing	Optimal
65	150082	149754	66318	61271
70	63802	59956	19623	19377
75	15309	15554	1773	1806
80	1169	1001	410	459
Fuel (kg)	79.9	79.5	56.4	56.0
NOx (kg)	964	956	615	607

4 Conclusions

A design space exploration tool was presented for the assessment of RNP AR approach procedures with a focus on the reduction of the noise-affected population. The exploration was limited to the horizontal flight path with the turn radii of the procedure's curved segments selected as the design variables. The vertical profile was only adapted to each procedure but otherwise remained unchanged. The results from the case study at Arlanda airport demonstrated that significant improvement could be achieved with minor adjustments to the original flight path, reducing the noise-affected population by approximately 5000 individuals.

The improved procedure was assessed under extreme weather conditions based on statistical data from the procedure location and showed increased noise impact compared to the standard conditions assessment. The selected weather conditions showed a strong impact on the noise due to the higher atmospheric temperature and the wind direction which resulted in a higher power requirement, suggesting that the optimal procedure may vary depending on the weather conditions.

The presented analysis was limited to a single flight and served as a feasibility study. A more comprehensive assessment of the noise benefits would require such an analysis to be performed under typical traffic conditions. Future research will, therefore, focus on this direction and on assessing the noise impact under different conditions, as the optimal procedure may vary between winter and summer. Finally, it is intended that the noise benefits will be evaluated in terms of their actual impact on the human health.

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