

Holistic Assessment of the Environmental Trade-offs of Novel Aircraft

Joy Stevens*

*Faculty of Engineering and Applied Sciences, Cranfield University, Cranfield, MK43 0AL, United Kingdom
Arup, London, W1T 4BJ, United Kingdom*

Ana Luisa Maldonado[†], and Tiffany Cheung[‡]
Arup, London, W1T 4BJ, United Kingdom

Anderson Proença[§]

Faculty of Engineering and Applied Sciences, Cranfield University, Cranfield, MK43 0AL, United Kingdom

This paper presents a high-level, scenario-based methodology for the integrated assessment of aircraft noise, CO₂, NO_x and PM_{total} emissions at an airport fleet level during standardised ICAO landing-and-take-off (LTO) operations. The approach extends a regression-based noise contour area model derived from ICAO certification data and calibrated against higher-fidelity modelling, and combines this with standard industry methods for CO₂ and air pollutant emissions to enable rapid comparison across different airport fleet mixes, incorporating different aircraft generations and novel propulsion technologies.

The methodology is applied to a UK airport case study to explore future fleet evolution pathways including technology progression and fleet renewal rates. The results show that the uptake of next-generation conventional aircraft reduces fleet-level noise, CO₂ and PM_{total} but increase NO_x emissions, whilst hydrogen and electric aircraft reduce fleet-level CO₂, NO_x and PM_{total} emissions but increase noise contour areas. These findings demonstrate that future fleet transitions may deliver uneven environmental improvements, highlighting the necessity of an integrated noise and emissions evaluation framework to support aircraft design decisions, airport planning, and policy development.

I. Nomenclature

A	Noise contour area, km ²
a	Vertical distance between ground point and aircraft flight path, m
b	Horizontal distance between ground point and aircraft flight path, m
c	Emission index, kg/kg fuel (CO ₂ and NO _x)
e	Engine operating mode
F_{oo}	Maximum sea level thrust, kN
$\dot{f}$	Fuel flow rate, kg/s
L	Fixed noise contour level, dB
N	Number of LTO movements
s	Constant relating to the slope derived from least-squares linear regression
t	Time, s
x	Ground distance from aircraft brake release point to noise contour along the runway centreline, m
y	Perpendicular ground distance from runway centreline to noise contour, m

Subscripts

$\square_T$	Takeoff noise certification point
-------------	-----------------------------------

*PhD student, Cranfield University, AIAA Member

[†]Senior Acoustics Consultant, Arup, AIAA Member

[‡]Senior Data Scientist, Arup

[§]Lecturer in Aerodynamics, Faculty of Engineering and Applied Sciences, Cranfield University

- _S Sideline noise certification point
- _A Approach noise certification point
- _i Individual flight mode i.e. taxi-out, climb, approach

II. Introduction

The aviation sector is simultaneously recovering from the disruption caused by the COVID-19 pandemic and transitioning toward long-term environmental sustainability. Although air traffic has steadily increased since 2020 and global passenger traffic has exceeded pre-pandemic levels, many regional airports remain below their 2019 passenger volumes [1, 2]. Notably, this recovery has been accompanied by a disproportionate rise in community noise complaints, even during periods of reduced operational activity [3]. This apparent contradiction is further complicated by the fact that individual aircraft have become substantially quieter [4] and since 2019, such aircraft have become increasingly prevalent in airport fleets [5].

At the same time, air quality and noise remain the two most significant environmental factors affecting community health, as recently identified by the House of Lords [6]. Exposure to poor air quality has been linked to stroke, heart disease and lung cancer [7], while adverse noise exposure is associated with cardiovascular disease, cognitive impairment, sleep disturbance and annoyance [8]. Consequently, noise and air quality impacts are typically among the primary drivers of community complaints, airport expansion objections and airspace change challenges, meaning these emissions can materially constrain airport operations.

In parallel, the industry is facing stringent decarbonisation targets, with global ambitions to achieve net-zero carbon emissions by 2050 [9–13]. Meeting these targets will require a combination of measures, including sustainable aviation fuels, carbon offsetting, airspace optimisation and aircraft technology improvements [14]. Technology improvements include electric or hydrogen propulsion, which can both necessitate and allow for novel airframe designs for fuel storage and propulsion.

Historically, aircraft and engine design changes such as increasing bypass ratios have delivered simultaneous reductions in fuel-burn and noise, with modern aircraft now around 40 dB quieter than the earliest commercial models [4]. These changes have also typically reduced pollutant emissions such as NO_x and particulate matter (PM). However, current aircraft designs are reaching a point where improvements in one environmental metric may result in adverse impacts in others [15].

Recent developments in aviation policy are starting to emphasize the need to address these emissions simultaneously. At the aircraft level, this was exemplified in the CAEP/13 outcomes, where more stringent noise and CO₂ emission limits were proposed simultaneously for the first time [16]. At the airport level, London Luton Airport was granted Government permission to expand operations by 70% under a new sustainability initiative called ‘green controlled growth’. This places legally binding annual limits on four environmental categories, including noise, CO₂ and NO_x [17]. Such precedents suggest that future regulation will increasingly require airports and aircraft manufacturers to demonstrate balanced environmental performance rather than optimisation against a single metric.

Despite this, multiple organisations have highlighted the difficulty of achieving simultaneous reductions in noise, air pollutant emissions and CO₂, and have emphasised the need for a quantitative understanding of the interdependencies and trade-offs associated with future aircraft technologies [18–20]. This was further demonstrated by a review [21] showing that predicted improvements in noise, NO_x and fuel-burn for various novel aircraft concepts failed to achieve all three NASA N+3 reduction targets concurrently. As future aircraft designs increasingly involve competing environmental objectives, it can no longer be assumed that newer aircraft will deliver meaningful noise reductions relative to today’s fleet. This places growing pressure on airports to understand how technology-driven trade-offs may affect local environmental performance and, ultimately, their social licence to operate.

This research builds upon previous work presented in [22] that addressed the need for an integrated assessment of environmental emissions at an airport fleet level involving novel zero-emission aircraft. The scenario-based framework has been extended here to include assessment of air pollutant emissions (NO_x and PM_{total}) in addition to the noise and CO₂ emissions assessed previously. While recent tools such as MONTANA [23] and RANE [24] enable noise prediction for novel aircraft using low-fidelity inputs, no existing approach efficiently quantifies noise, CO₂ and air pollutant emissions together or explicitly explores their trade-offs for future fleet compositions. The methodology presented is therefore used to explore multiple future fleet compositions and technology adoption pathways, allowing a fully holistic environmental assessment to be rapidly undertaken at an airport fleet level.

III. Methodology

A. Noise Emissions

This work extends a previous study [22], which developed a high-level noise prediction methodology to undertake noise contour area predictions at an airport fleet level based on the individual aircraft's ICAO certification noise levels at the three standard certification points. This enabled the rapid estimation of changes in airport noise contour area arising from variations in fleet composition and operational frequency. The certification measurement positions are defined in Table 1.

Certification point	Location
Takeoff, T	6.5km from the brake release position along the runway centreline, x_T
Sideline, S	450m laterally from the runway centreline at the location of peak noise during takeoff (measured in 100m intervals from start of roll position), y_S
Approach, A	2km before the touchdown point along the runway centreline, x_A

Table 1 ICAO-defined noise certification measurement positions

The noise contour is assumed to be a generalized elliptical shape, symmetric about the runway axis, corresponding to a fixed noise level L along its perimeter. The method assumes the aircraft fly under constant operational conditions, such as continuous climb or descent angles, aircraft settings (e.g. deployment of landing gear, flaps), thrust levels, and therefore constant acoustic output.

Full details of the governing equations and derivations can be found in [22], with an overview provided here for completeness. Using spherical sound propagation principles, the maximum distances (x, y) to a given contour are related to the logarithmic sum of noise levels of all considered aircraft movements determined at the certification points (L_T , L_S , and L_A) and the known distances to these points. The geometric configuration of a representative departure operation is illustrated in Figure 1, reproduced from [25].

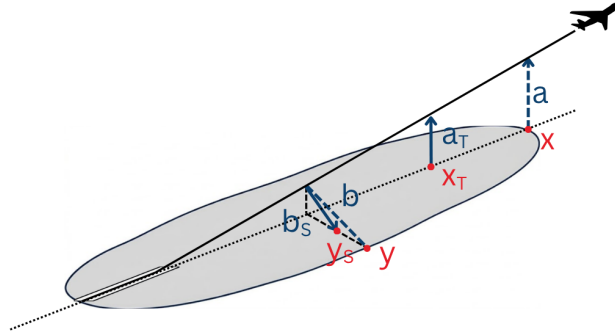


Fig. 1 Illustration of the generalized departure noise contour and associated geometric parameters. Reproduced from [25], where subscript T denotes takeoff and subscript S denotes sideline certification points.

The contour area, A , is then considered to be related to the product of these distances, the noise level along the contour perimeter and the total noise levels at the certification points. The variation in noise contour area can then be found from the change in aircraft fleet source noise level (defined at the certification points) and a constant, s . This constant is an empirically determined coefficient describing the relationship between the certification noise level and contour area, derived from regression analysis against higher fidelity modelling predictions using existing tools such as the FAA's AEDT.

To determine the constant s , a selection of aircraft was chosen to represent the spectrum of airframe sizes and propulsion systems commonly currently operated at major airports. This mainly consisted of aircraft that achieved the

ICAO Chapter 4 and Chapter 14 noise limits. A full list of the aircraft used for this analysis is presented in Appendix I. For each aircraft, the predicted noise contour area and noise level at each certification point was determined for a single departure operation using AEDT. A total of 90 combinations of input variables was run through a least-squares linear regression algorithm. The parameters used for the input variables are detailed in Table 2. Figure 2 shows example outputs of the relationships for the 102 dB SEL noise contour.

Certification point	Certification noise level	Noise contour metric	Noise contour level
T	Measured	EPNL	85 dB
S	AEDT predicted EPNL	SEL	90 dB
T+S	AEDT predicted SEL		95 dB
			100 dB
			102 dB

Table 2 Parameters used for least-squares linear regression analysis

B. Gaseous and Particulate Emissions

The method used for determining CO₂, NO_x and PM emissions has been taken from the standard industry method introduced in EEA Report 06/2023 [26] and described in Part B: 1.A.3.a Aviation 2023 of the report. Engine fuel burn and emissions data were sourced from the ICAO Aircraft Engine Emissions Databank [27] and the Swedish Defence Research Agency (FOI) Turboprop Emissions Database [28].

Typically 75% - 95% of an aircraft's fuel is burnt during the cruise, climb and descent (CCD) phases of flight rather than during the landing and take-off cycle (LTO) [29]. The exact amount is of course highly dependent on the route of each aircraft. The LTO cycle is a well-defined, standardized profile used for engine certification. It is defined to encompass all aircraft operations conducted up to 3000ft above ground level [30]. It is divided into four distinct engine operating modes, summarized in Table 3. Because of the higher thrust requirements during take-off, the LTO cycle uses greater fuel burn per unit distance compared to the CCD phase [26].

As there is significant variation in route distances between airports, and airports can alter their destination offerings (and therefore route distances) over time in response to passenger demand, this work has only considered the emissions generated as part of the LTO cycle. The dependence on aircraft destination is therefore removed, allowing for direct comparisons between aircraft fleets and airports.

Operating mode	Thrust setting	Time in operating mode (s)
Take-off	100% F_{oo}	42
Climb-out	85% F_{oo}	132
Approach and landing	30% F_{oo}	240
Taxi-in / taxi-out	7% F_{oo}	1140 / 420

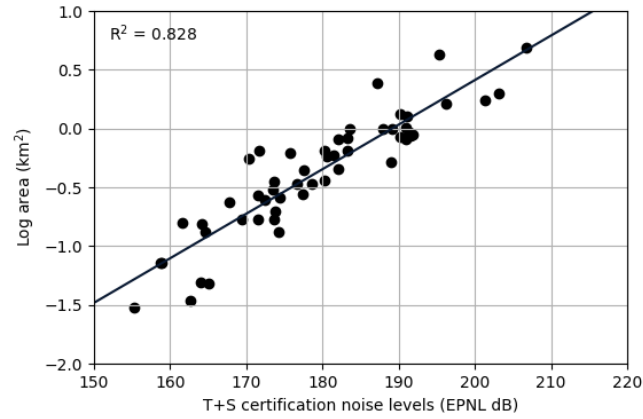
Table 3 Different operating modes in the LTO cycle, their engine thrust setting as a percentage of maximum sea level thrust (F_{oo}) and the ICAO default time spent in each mode [30].

1. CO₂ and NO_x Emissions

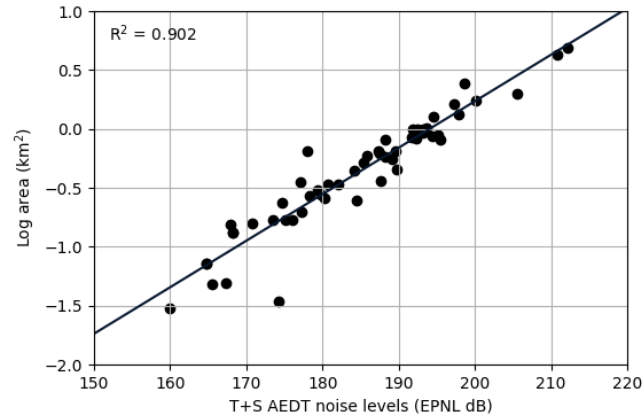
The CO₂ and NO_x emissions generated during the LTO cycle for each aircraft type were calculated using Equation 1:

$$\text{Emissions (kg)} = N \cdot \left(\sum_i \dot{f}_i t_i e_i \right) \cdot c_i \quad (1)$$

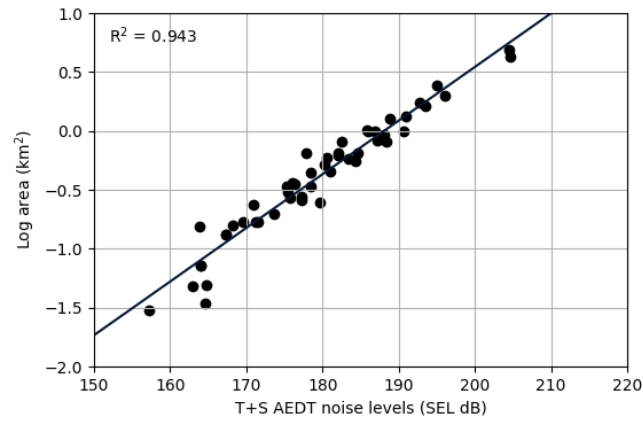
where i represents each of the LTO cycle modes defined in Table 3, N is the total number of LTO movements for the aircraft type, $\dot{f}_i$ is the fuel flow rate in mode i (kg/s), t_i denotes the duration of that mode (s), and e_i is the number of engines operating per mode. The constant c corresponds to the CO₂ or NO_x emission index, which specifies the mass of



(a) Measured EPNL noise levels at certification points



(b) Predicted EPNL noise levels at certification points



(c) Predicted SEL noise levels at certification points

Fig. 2 Relationship between the 102 dB SEL noise contour area and the sum of noise levels at the takeoff (T) and sideline (S) certification points. For each relationship, the variance is shown (the square of the correlation coefficient, R)

the compound released per kilogram of fuel burned, kg/kg fuel. The CO₂ emission index is dependent on the type of aviation fuel used and is therefore constant during all modes. For conventional kerosene, this has a value of $c = 3.15$ [31]. The NO_x emission index is dependent on engine design parameters and operating conditions, therefore the value of c varies with the engine model and operational mode. Specific values for $\dot{f}_i$ and c_i were taken from the ICAO emissions database and the FOI emissions databank mentioned above. ICAO also provides the historical annual average time spent in each operating mode for various European airports, as well as ICAO default times (shown in Table 3).

The total quantity of CO₂ and NO_x produced for the airport as a whole was then determined by evaluating Equation 1 for each aircraft type and summing the results for the entire fleet mix.

2. Particulate Matter Emissions

The total PM emission index (PM_{total}) consists of three separate components: non-volatile PM, volatile sulphate PM and volatile organic PM. Non-volatile PM consists predominantly of soot particles, commonly referred to as elemental or black carbon, formed during incomplete combustion. These particles are emitted directly at the engine exhaust and are strongly influenced by combustor design, engine operating conditions, and fuel composition. Volatile PM, including sulphate-dominated and organic-dominated components, is formed downstream of the engine where the exhaust plume cools and dilutes. In this region, sulphuric acid (for volatile sulphate PM) and unburned hydrocarbons or semi-volatile organic compounds (for volatile organic PM) condense onto existing non-volatile particles or nucleate to form new volatile particles. The formation of both volatile PM components therefore depends on engine operating conditions and the thermodynamic evolution of the exhaust plume during cooling and dilution. Volatile sulphate PM is additionally influenced by the fuel sulphur content, whereas volatile organic PM depends on the amount of unburned hydrocarbons and semi-volatile organic compounds present in the exhaust following combustion [32].

PM emissions generated during the LTO cycle for each aircraft type were estimated using Equation 1. As the required emission indices (c_i) are not reported directly in the ICAO emissions database or the FOI emissions databank, the calculation workflow shown in Figure 3 was used to derive the total emissions index values. This workflow follows the methodology presented in the ICAO Airport Air Quality Manual [33]. The input information (top level boxes) was taken from the ICAO and FOI databanks.

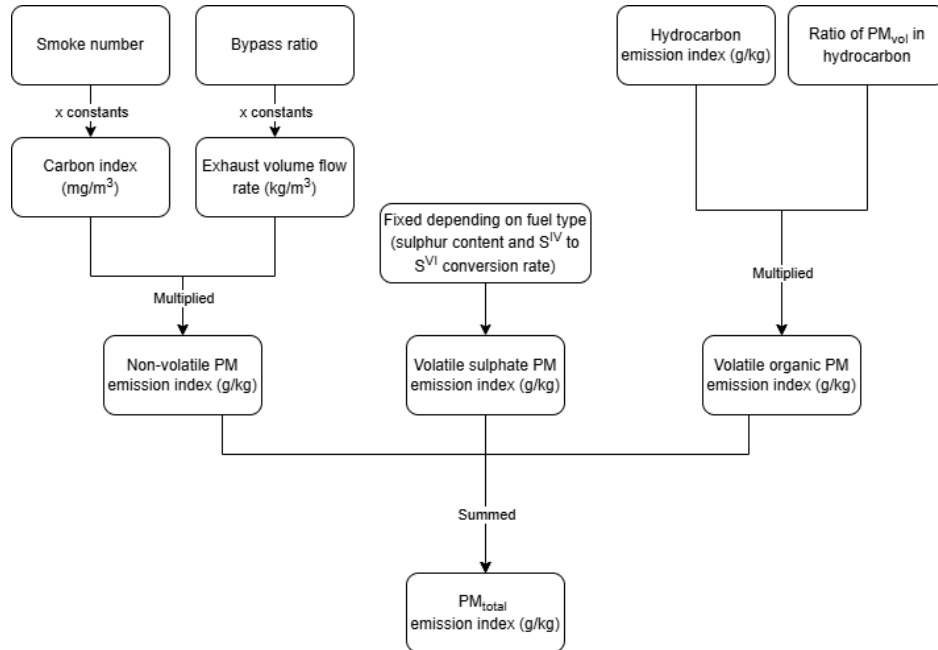


Fig. 3 Calculation workflow to determine the PM_{total} emission index, following the methodology presented in [33]

Similarly to the CO₂ and NO_x emissions, the total quantity of PM produced for the airport was also determined through summing the outputs of Equation 1 for each aircraft type across the whole fleet.

IV. Test Case

The methodology presented here has been applied to a case study of a particular UK airport. Assumptions were provided by the following sources to enable a realistic (though hypothetical) assessment to be undertaken:

- The airport provided the current fleet mix and forecast growth assumptions for each aircraft class for the period 2026–2056. The analysis was limited to commercial aircraft only and the aircraft class categories were aligned with Sustainable Aviation guidance [34].
- Airlines provided projected fleet renewal timelines indicating when legacy aircraft are expected to be fully replaced by newer-generation models (e.g. Airbus A320neo family, Boeing 737 MAX, Embraer E190-E2). Where such information was not disclosed directly by airlines, fleet renewal timelines were derived from publicly available sources, such as [35–41].
- Assumptions around future conventional and zero-emission aircraft concept definitions and projected entry-into-service (EIS) dates were developed based on publicly available information from aircraft manufacturers and industry stakeholders [42–51]. The assumed EIS dates used are based on indicative timelines developed for analytical purposes, rather than confirmed development or certification schedules. An overview of the technologies and EIS dates assumed for this work is shown in Figure 4.
- Uptake rates for next-generation aircraft were derived from historical fleet transition rates observed at the airport and more broadly in the industry [52], specifically the adoption of the Airbus A320neo family relative to the A320ceo variants, and the Boeing 737 MAX relative to earlier 737 variants. Two uptake scenarios were assessed: one reflecting the historically observed transition rates, and a second assuming an accelerated renewal rate, with fleet replacement occurring over half the historical transition period.

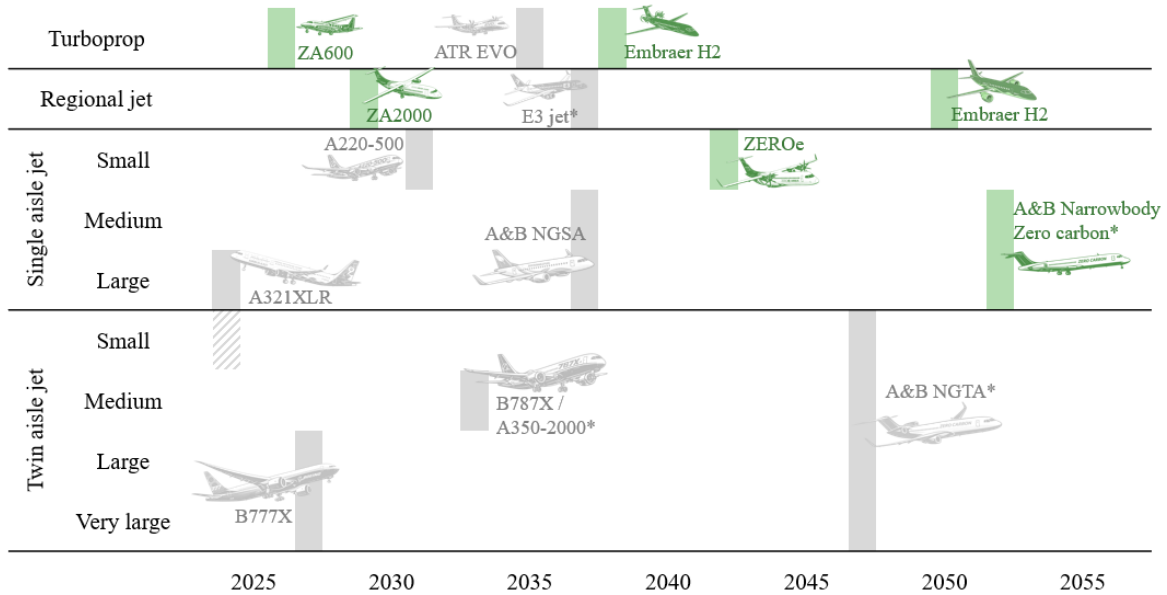


Fig. 4 Assumed entry-into-service dates for ultra-efficient (grey) and zero-emission (green) aircraft technologies, based on [42–51]. The EIS dates for aircraft with an asterisk (*) have been assumed to EIS roughly 15-20 years after their previous counterparts

Sixteen aircraft types were found to account for approximately 85% of the total aircraft movements at the airport. To simplify the analysis, all remaining aircraft were represented using one of these 16 proxy models. All proxy aircraft were included in the linear regression analysis described above. These aircraft types were subsequently grouped into eight aircraft classes, in accordance with Sustainable Aviation guidance. Figure 5 summarises the fleet mix and airport operations assumed for this case study.

Assumed uptake rates for next-generation aircraft were informed by historic and airline-forecasted fleet renewal patterns observed for the Airbus A320neo family relative to the A320ceo, and the Boeing 737 MAX relative to earlier 737 variants. Figure 6 presents the proportion of next-generation aircraft within the fleet as a function of time relative to

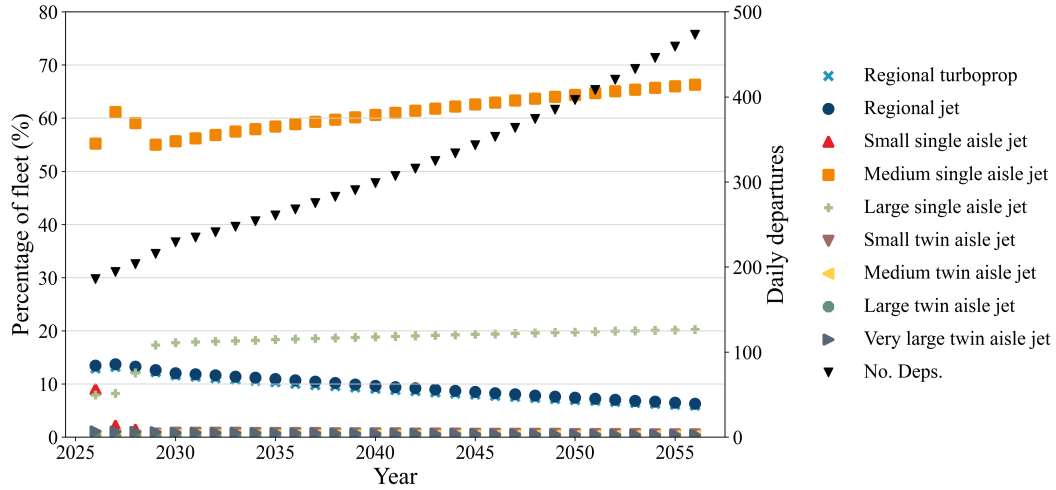


Fig. 5 Forecast operations between 2026-2055 for the studied airport

the aircraft type's EIS year, accounting for the recertification and delayed introduction of the 737 MAX.

For this airport, the historic data indicated that next-generation aircraft began to appear in the operational fleet approximately two years after EIS, with full fleet renewal occurring over a period of approximately 20 years from EIS. In addition to this historic uptake profile, an accelerated renewal scenario was defined, assuming fleet replacement occurs at twice the historic rate, resulting in a total renewal period of 10 years. These scenarios are referred to hereafter as the historic and faster uptake rate scenarios, respectively.

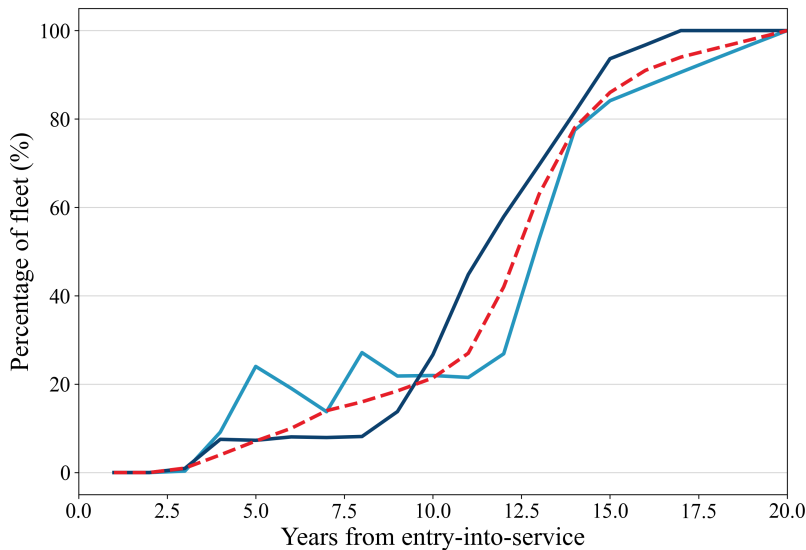


Fig. 6 Historic uptake rate of the new Airbus (light blue line) and Boeing (dark blue line) aircraft relative to the entry-into-service year, and the generalized uptake rate assumed for this work (red dashed line)

This work has assumed that there are no changes to the operational flight profile of the aircraft. The flight profiles assumed are those used for the noise certification measurements. It also assumes that the passenger capacity of future generation aircraft remains the same.

V. Results and Discussion

A. Verification Against AEDT

The noise contour area prediction methodology was verified against AEDT for this particular case study. Daily noise contour areas were modelled using both the proposed method and AEDT for each year between 2026 and 2030, adopting the forecast operational fleet mix shown in Figure 5. This period was selected as fleet composition changes outside these years are relatively modest and therefore these years were thought to be representative for the full forecast period.

The modelling results were also used to identify the most appropriate linear regression relationship, s , to use in the calculations, as detailed in Section III.A. All 90 regression coefficients were evaluated, and these were applied to certification noise levels derived from three methods (measured Effective Perceived Noise Levels (EPNL), AEDT-predicted EPNL values, and AEDT-predicted Sound Exposure Level (SEL) values), resulting in 270 combinations assessed overall.

To compare this modelling approach with AEDT, the percentage change in noise contour area was calculated for each forecast year relative to the 2026 baseline year using both models, and all 270 combinations were tested against AEDT. The combination that resulted in the lowest and most consistent difference between both methods was chosen for the subsequent analysis. The difference between modelling results using the selected combination and AEDT is shown in Figure 7.

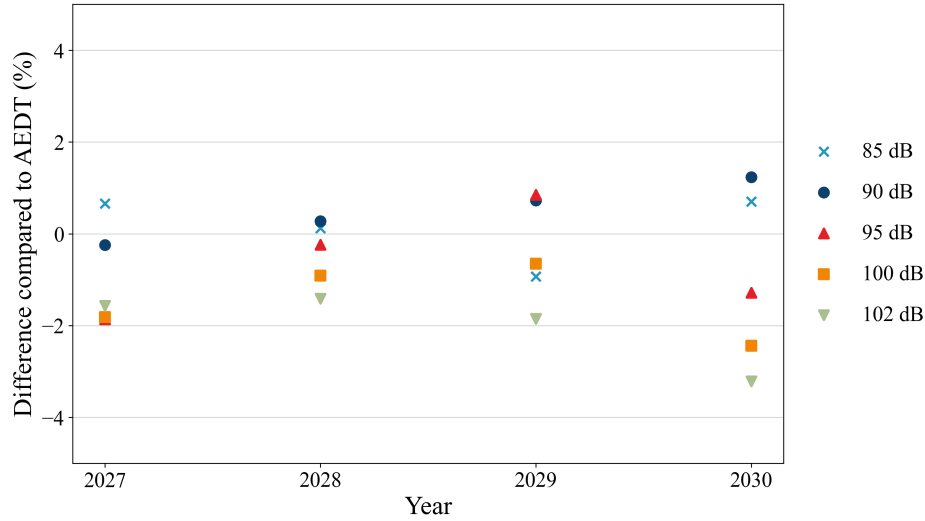


Fig. 7 Difference in noise contour area of this method compared to AEDT

Across all modelled SEL contour bands, the absolute difference in the predicted percentage change in noise contour area between the two methods was found to be less than 3.2%. In the UK, airport noise assessments typically use the $L_{Aeq,16hour}$ noise metric, which is defined as the A-weighted equivalent continuous sound level over the 16-hour period between 07:00-23:00. The UK Government is particularly interested in the 54 $dB L_{Aeq,16hour}$ noise contour level as it has been identified as the threshold for the onset of community annoyance [3, 53]. 54 $dB L_{Aeq,16hour}$ translates to an SEL of 102 dB. For the airport considered in this study, the associated errors at this SEL contour were comparable to those observed across other bands. Therefore, all subsequent results presented in this paper are reported for the 102 dB SEL contour.

CO_2 , NO_x and PM_{total} emissions for this case study were calculated using established, published methodologies, and as such no formal error propagation or model-specific uncertainty analysis was undertaken for these emission estimates. Consequently, uncertainty in the reported emissions is primarily driven by the assumptions underpinning the future scenarios considered, including aircraft technology characteristics, projected fleet composition, and assumed entry-into-service timelines.

B. Future Fleet Scenarios

Using the case study and assumptions presented above, four fleet evolution scenarios were analysed. The definitions of aircraft generations have been based on Sustainable Aviation's definition [14] of current (G0), imminent (G1) and future (G2) aircraft as of 2014. G1 aircraft include those already in service, such as the Neo's and MAX's, as well as the imminent Boeing 777X.

- Baseline scenario - aircraft are updated to G1 technology and then no further updates are made
- Conventional upgrade scenario - aircraft are updated to G1 and G2 technologies, with aircraft retaining conventional design and propulsion mechanisms. These aircraft will be ultra-efficient, experiencing emissions reductions through advances in traditional mitigation options
- Electric upgrade scenario - electric aircraft are introduced to the fleet as and when they become available. Due to the technological and weight implications of electric aircraft, these are assumed to only be realistic for regional turboprop and regional turbojet aircraft
- Hydrogen upgrade scenario - hydrogen aircraft are introduced to the fleet as and when they become available. Similarly to electric aircraft, there are limitations to the size of hydrogen aircraft and this work has assumed that regional turboprops, regional jets, and small/medium/large single aisle jets will eventually be powered by hydrogen propulsion mechanisms.

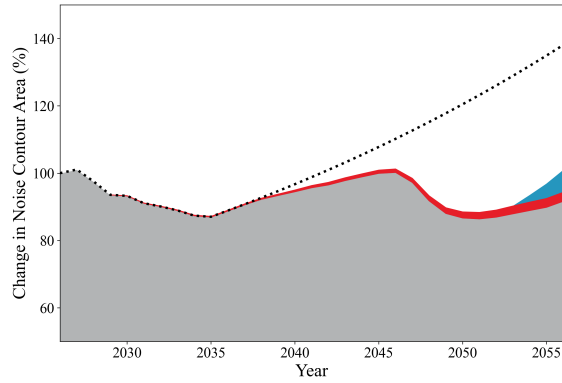
Each of the four scenarios above were modelled with two fleet renewal rates: historic and faster, as described in Section IV. All aircraft have been assumed to upgrade to their respective G1 and G2 technologies at the same rate (shown in Figure 6, although the entry-into-service dates differ).

For each scenario, noise, CO₂, NO_x and PM_{total} emissions have been predicted to demonstrate the intended use of this method. Noise levels for G1 and G2 aircraft have been based on those used for the Sustainable Aviation work, as well as existing certification data for G1 aircraft models where available (such as for the Airbus Neo's and Boeing MAX's). CO₂, NO_x and PM_{total} emission indices similarly have been based on available certification data for G1 aircraft. Conventional G2 aircraft are assumed to have the same percentage improvement in the fuel burn rates and emission indices across successive aircraft generations and therefore values have been extrapolated from G0 and G1 aircraft types. G2 zero-emissions aircraft are assumed to have zero tailpipe CO₂, NO_x or PM_{total} emissions (i.e. assuming fully electric or hydrogen fuel cell aircraft).

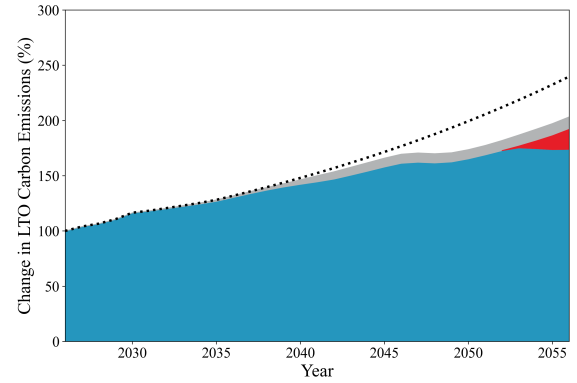
1. Historic Renewal Rate Results

The predicted change in all four environmental emissions compared to a 2026 baseline year was determined for the scenarios described above and the results are presented in Figure 8.

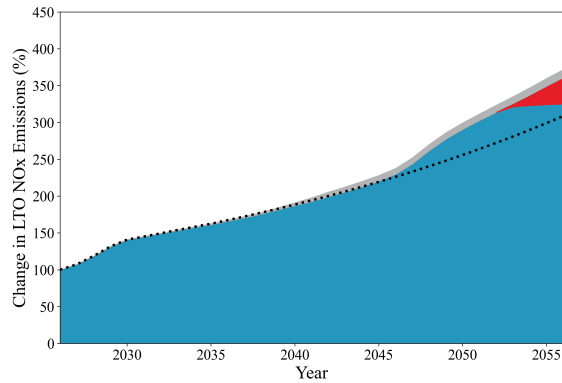
Figure 9 shows the percentage of the fleet that is each generation (G0, G1, G2) during the forecast period, as well as the percentage of the fleet that is assumed to be electric and hydrogen aircraft (for the respective scenarios).



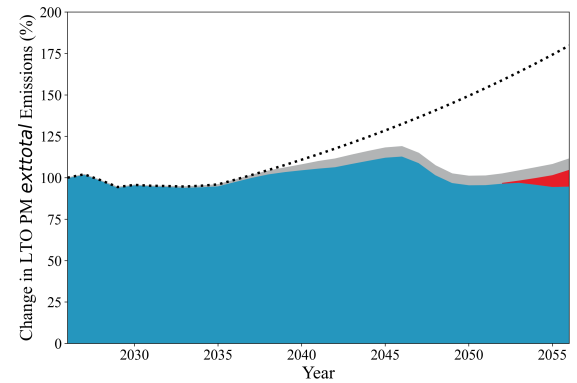
(a) Noise contour area



(b) CO₂ emissions

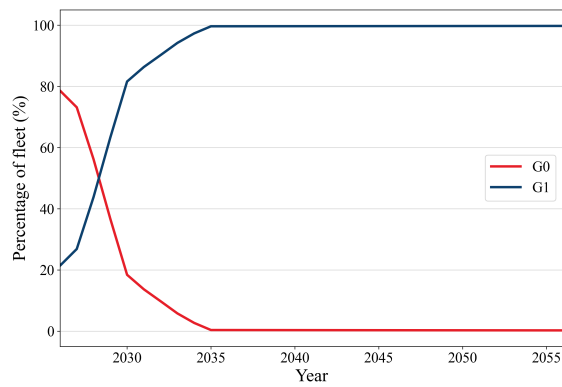


(c) NO_x emissions

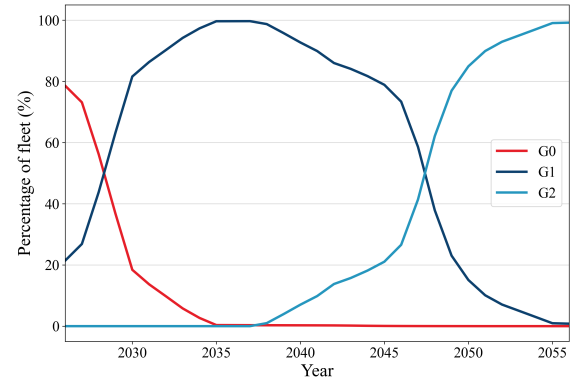


(d) PM_{total} emissions

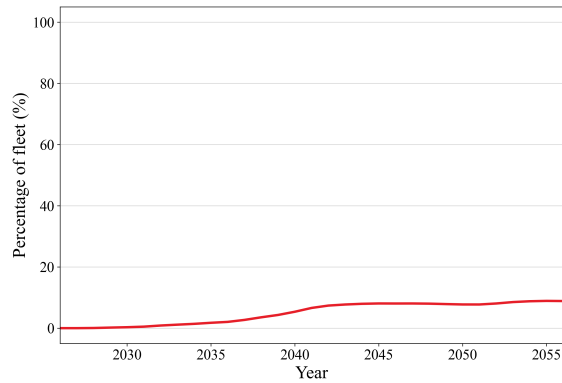
Fig. 8 Percentage change in the airport's environmental emissions compared to a 2026 baseline year, assuming fleet renewal to next-generation aircraft occurs at the same rate as historical renewals. Scenarios shown are the baseline (dotted black line), conventional upgrade (grey shaded area), electric upgrade (red shaded area) and hydrogen upgrade (blue shaded area).



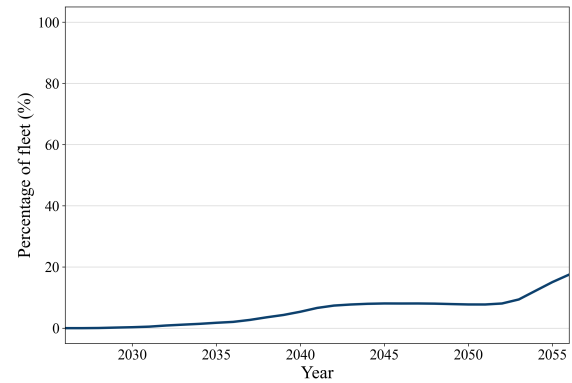
(a) Modelled uptake rates of next generation (G) aircraft for the baseline scenario only



(b) Modelled uptake rates of next generation (G) aircraft for the conventional, electric and hydrogen upgrade scenarios



(c) Percentage of electric aircraft assumed for the electric upgrade scenario



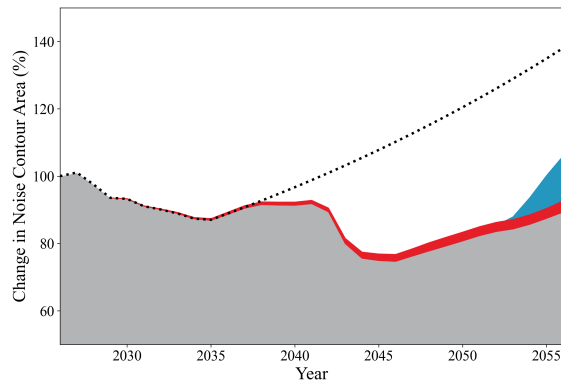
(d) Percentage of hydrogen aircraft assumed for the hydrogen upgrade scenario

Fig. 9 Modelled fleet mix, in terms of aircraft generation and novel propulsion technology type

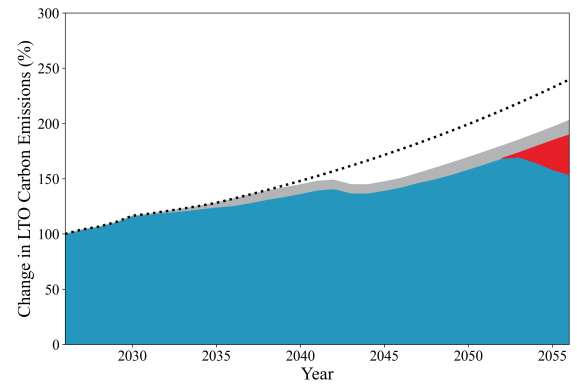
2. Faster Renewal Rate Results

The predicted change in all four environmental emissions compared to a 2026 baseline year was determined for the scenarios described above and the results are presented in Figure 10.

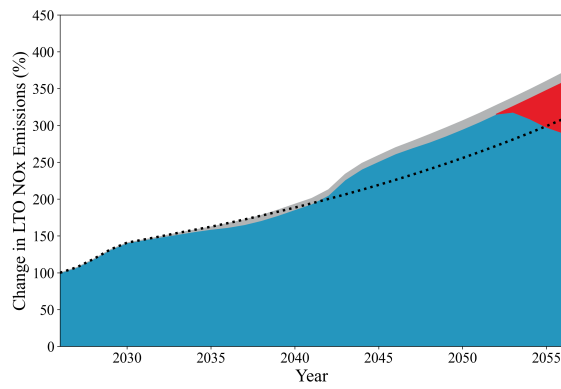
Figure 11 shows the percentage of the fleet that is each generation (G0, G1, G2) during the forecast period, as well as the percentage of the fleet that is assumed to be electric and hydrogen aircraft (for the respective scenarios).



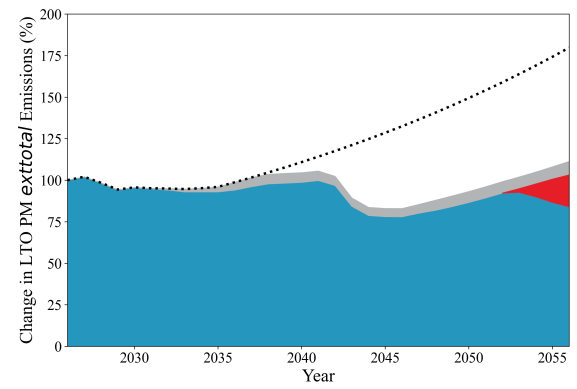
(a) Noise contour area



(b) CO₂ emissions

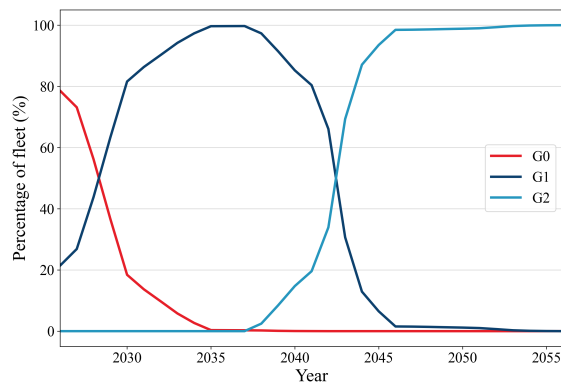


(c) NO_x emissions

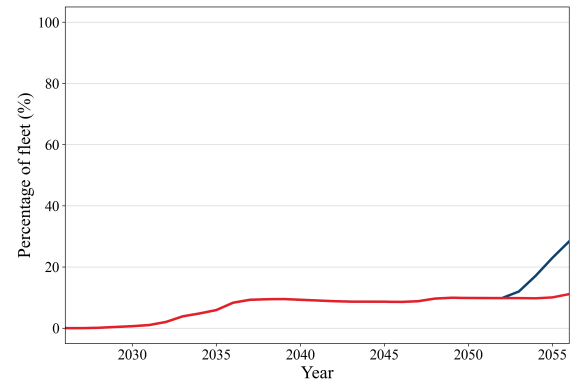


(d) PM_{total} emissions

Fig. 10 Percentage change in the airport's environmental emissions compared to a 2026 baseline year, assuming fleet renewal to next-generation aircraft occurs at a faster rate than historical renewals



(a) Modelled uptake rates of next generation (G) aircraft for the conventional, electric and hydrogen upgrade scenario



(b) Percentage of electric and hydrogen aircraft assumed for the respective upgrade scenarios

Fig. 11 Modelled fleet mix for the faster renewal scenario, in terms of aircraft generation and novel propulsion technology type

C. Discussion

1. Impact of Technology Upgrades

The results presented in Figure 8 show that freezing the fleet technology after G1 aircraft have fully replaced G0 aircraft with an increasing number of movements (baseline scenario) leads to overall increases in all the emission types by the end of the forecast period, proportional to the increase in the number of movements. As the aircraft technology remains unchanged in this scenario, this result is expected. Noise and PM_{total} emissions decrease until around 2035, as the proportion of G1 aircraft in the fleet is still increasing and the technology improvements for these two emissions outweigh the increase in the number of movements. CO_2 and NO_x emissions still increase during this period as the technology improvements are not large enough to offset the growth in traffic.

Updating the fleet with conventional G1 and G2 aircraft reduced the noise, CO_2 and PM_{total} emissions by the end of the forecast period by approximately 50%, 40% and 70% respectively compared to the baseline scenario. G2 aircraft were modelled to enter the fleet in 2037, and this can be seen by the deviation from the baseline scenario from this year onwards. The overall noise contour area is predicted to be slightly smaller by the end of the forecast period when compared to the baseline year of 2026. CO_2 and PM_{total} see an overall increase in emissions at the end of the forecast year compared to 2026. However NO_x emissions see an overall increase compared to both the baseline year (2026) and to the baseline scenario. This is because as engines are designed to reduce fuel burn and increase thermodynamic efficiency, the overall pressure ratio tends to increase which increases the combustion temperature within the engine [54]. Higher temperatures promote the formation of NO_x as the nitrogen and oxygen in the air react more readily at elevated temperatures.

Introducing electric aircraft results in a small overall reduction in CO_2 , NO_x and PM_{total} emissions by the end of the forecast period, however it results in a small increase in the overall noise levels. The small changes that are shown are due to the fleet mix of the airport only containing around 10% of aircraft that could conceivably be replaced with electric aircraft.

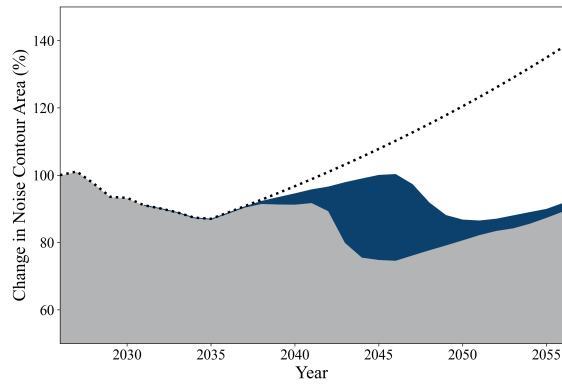
Hydrogen aircraft show the same trends as electric aircraft however the effect is more pronounced from 2052 onwards, as that is when the hydrogen-powered single aisle jets are assumed to enter into service. These make up a large majority of the airport's fleet mix and represent an additional aircraft class that can be made zero-emission over the electric counterparts, therefore causing the exaggerated increases and decreases in the various emissions.

The overall noise contour area for the electric and hydrogen scenarios increases compared to the conventional aircraft scenarios because zero-emission aircraft are expected to be powered by electric batteries and hydrogen fuel cells, which can significantly increase the aircraft's overall weight. The added mass leads to higher thrust requirements during take-off, elevating the engine power settings and therefore the noise output. As a result, despite the cleaner energy sources, these aircraft are shown to produce greater noise contour areas during departure operations compared to conventional aircraft.

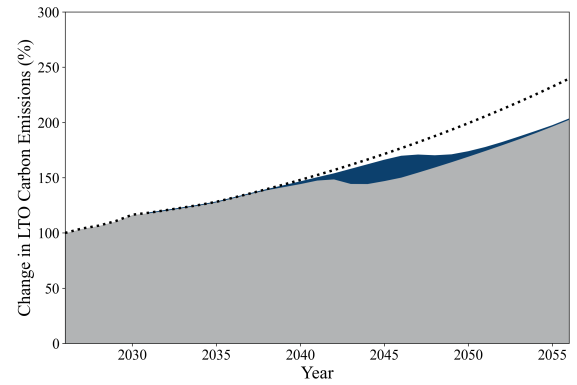
2. Impact of Fleet Renewal Rate

Figure 10 shows the same four scenarios as Figure 8 but assuming the faster uptake rate of 10 years for fleet renewal, compared to the historic rate of 20 years. It can be seen that the overall conclusions are the same for all emissions types, however the undulations in the charts are shifted to an earlier year and the peaks are more pronounced. This is expected as the change in technology - and therefore all emissions - is exaggerated.

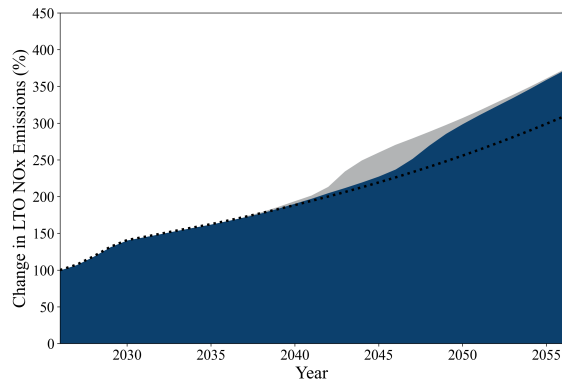
To further demonstrate the impact of fleet renewal rates on an airport, the historic and faster renewal rate results are presented in the same chart for the conventional upgrade scenario (Figure 12). Here we can clearly see a roughly 10 year period between 2040 to 2050 where there is a measurable benefit of reduced noise, CO_2 and PM_{total} emissions. This would result in a defined respite period for the local community in terms of noise and PM_{total} emissions that they otherwise would not experience. However, during the same period, the increase in NO_x emissions represents a trade-off in air pollutant emissions.



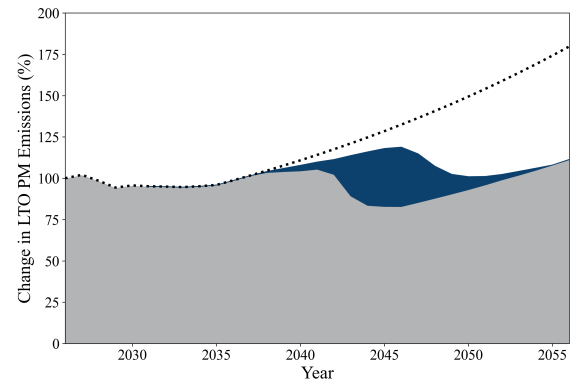
(a) Noise contour area



(b) CO₂ emissions



(c) NO_x emissions



(d) PM_{total} emissions

Fig. 12 Difference in the airport's emissions for the conventional upgrade scenario, comparing the historic (20 year, dark blue shaded area) and faster (10 year, grey shaded area) fleet renewal rates. The dotted black line shows the baseline scenario with the historic renewal rate.

VI. Conclusions and Future Work

This research has introduced and demonstrated the applicability of a rapid, integrated methodology for assessing aircraft noise, CO₂, NO_x and PM_{total} emissions at an airport fleet level. The noise prediction approach has been shown to closely approximate AEDT noise contour areas for the case study airport, as demonstrated by the 102 dB SEL contour showing errors of less than 3.2% compared to AEDT.

Application of the methodology to a UK airport case study has demonstrated that future fleet evolution paths can produce distinct environmental outcomes depending on both the technologies adopted and the fleet renewal rate.

Conventional upgrades to more efficient G1 and G2 aircraft delivered fleet-level reductions in noise, CO₂ and PM_{total} emissions, but resulted in increased NO_x. Similarly, electric and hydrogen aircraft offered substantial reductions in CO₂ and air pollutant emissions, while being associated with increased departure noise. These results demonstrate that future aircraft technologies cannot be assumed to deliver simultaneous improvements across all environmental metrics. Faster fleet renewal rates provided temporary periods of reduced noise and PM_{total} emissions, offering potential community respite, but also increased adverse trends for NO_x emissions.

More broadly, this work has addressed a critical gap in both academic literature and industry practice by providing a quantitative framework to assess the trade-offs and interdependencies between noise, CO₂ and air pollutant emissions (NO_x and PM_{total}) for future aircraft. The case study assessed here has shown that no scenario results in an overall reduction in all emission types simultaneously at an aircraft fleet level, demonstrating the necessity of considering these emissions in combination.

The methodology presented in this paper therefore offers a transparent and computationally efficient tool, enabling airports, policymakers and industry stakeholders to explore the environmental trade-offs associated with future fleet strategies. This ultimately allows them to make informed decisions that balance competing environmental objectives whilst maintaining their long-term social licence to operate.

Appendices

Part I

Aircraft Selection

Table 4 Overview of the aircraft used for this work

AEDT ID	Manufacturer	Model	Engine model	AEDT TOW (1000kg)	Takeoff Noise (EPNdB)	Sideline Noise (EPNdB)	Approach Noise (EPNdB)
AT72	Aerospatiale	ATR 72-212 A	PRATT & WHITNEY CANADA PW127F, PW127M	22.8	80.2	82.5	92.2
A319	Airbus	A319-131	V2522-A5	64.0	85.3	91.4	94.5
A320	Airbus	A320-211	CFM56-5A1	73.5	87.8	94.3	96.4
A320N	Airbus	Airbus A320neo	LEAP-1A26/26E1	79.0	81.5	86.2	92.2
A321	Airbus	Airbus A321-100	CFM56-5B1	89.0	89.5	96.2	96.8
A321n	Airbus	Airbus A321neo	LEAP-1A35A/33/33B2/32/30	89.0	82.1	88.9	94.0
A310	Airbus	A310-304	CF6-80C2A2	150.0	92.9	96.1	98.8
A300	Airbus	A300B4-203	CF6-50-C2	161.9	94.0	96.9	102.4
A30062	Airbus	A300B4-622R	PW-4158	170.5	93.1	97.9	101.9
A330	Airbus	A330-301	CF6-80E1A2	211.8	94.2	97.2	98.7
A340	Airbus	A340-212	CFM56-5C3	257.0	96.1	95.4	97.2
A350	Airbus	Airbus A350-900	Trent XWB-84	277.0	86.0	91.5	96.4
A380	Airbus	Airbus A380-800	Trent 970-84	569.0	95.6	94.2	98.0
BAE146	BAE Systems	146-200A	ALF502R-5	41.3	85.2	87.3	95.8
737N17	Boeing	B-737-200 ADV (NOR- DAM; STC ST00131SE)	JT8D-17/-17A w/LGW Hushkit	47.6	89.7	97.5	96.0
717200	Boeing	B-717-200	BR700-715C1-30 (MP)	54.9	82.2	91.5	92.1
737300	Boeing	B-737-300	CFM56-3-B1	63.0	87.5	89.9	100.1
737800	Boeing	B-737-800	CFM56-7b27/2b1 DAC	78.2	85.9	94.3	96.8
7378	Boeing	Boeing 737 MAX 8	LEAP-1B28BBJ1	82.2	82.6	88.5	94.2
727EM2	Boeing	B727-200 (FED EX; STC SA5839NM)	JT8D-15 w/Burbank inlet + fan CSD	85.7	97.7	97.6	98.6
757PW	Boeing	B-757-200	RB211-535E4-B	94.8	86.2	94.0	95.0
757300	Boeing	B-757-200	PW 2037	100.7	88.4	94.8	97.7
757200	Boeing	Boeing 757-200	RRB211-535E4B	115.7	86.2	93.8	95.2
757RR	Boeing	B-757-300	RB211-535E4-B	122.2	81.3	94.4	95.4
767300	Boeing	B-767-300	PW 4060	166.8	93.2	97.0	100.2
767400	Boeing	B-767-400	CF6-80C2B8F	191.6	91.2	96.8	98.7
7878	Boeing	Boeing 787-8 Dreamliner	GENx-1B64/P2	227.9	88.3	90.3	95.7

Continued on next page

AEDT ID	Manufacturer	Model	Engine model	AEDT TOW (1000kg)	Takeoff Noise (EPNdB)	Sideline Noise (EPNdB)	Approach Noise (EPNdB)
777200	Boeing	B-777-200	GE90-76B	242.7	88.8	93.2	97.8
7879	Boeing	Boeing 787-9 Dreamliner	GENx-1B74/75/P2	254.0	89.4	92.7	97.0
747SP	Boeing	B-747-SP	JT9D-7A	283.5	102.0	101.1	102.9
777300	Boeing	B-777-300	RR TRENT 892	288.5	94.2	96.9	100.4
74720B	Boeing	B-747-200	JT9D-7Q	351.5	103.2	103.5	106.6
747400	Boeing	B-747-400	PW4056	382.5	101.6	99.7	104.7
CL600	Bombardier	CL-600	ALF-502L/L-2/L-2C	16.3	84.7	89.5	91.6
CL60	Bombardier	Bombardier Challenger 650	2xGE CF34-3B	21.9	79.0	85.6	91.3
C25A	Cessna	CESSNA 525A / Citation-Jet CJ2	WILLIAMS INTERNATIONAL FJ44-3A-24	5.7	75.5	86.1	89.7
CNA55B	Cessna	550 Citation Bravo	PW530A	6.7	73.7	85.2	91.2
CNA750	Cessna	750 Citation X	AE3007C	16.2	72.3	83.0	90.2
E55P	Embraer	Embraer 505 Phenom 300	Pratt & Whitney Canada PW535E	8.2	69.9	88.8	88.9
E145	Embraer	EMB-145EP	2 x ALLISON AE 3007/A1/I	21.0	80.1	85.0	92.6
EMB14L	Embraer	EMB-145LR	AE3007A1/I	22.0	79.4	84.6	92.5
E170	Embraer	Embraer 170-200STD	CF34-8E5	36.0	80.8	90.7	95.2
E190	Embraer	ERJ 190-100 SR	GENERAL ELECTRIC CO CF34-10E5A1 G07	46.0	81.4	93.0	91.8
F10065	Fokker	F100	TAY MK650-15	43.6	81.8	91.7	93.0
GIV	Gulfstream	G-IV	TAY 611-8	28.8	76.8	87.3	91.0
GV	Gulfstream	G-V	BR700-710A1-10	34.9	80.3	89.1	90.8
IA1125	Israel Aircraft	1125 Astra	TFE731-3A-200G	10.7	84.1	89.7	89.8
L10115	Learjet	35A/36A	TFE731-2-2B	8.3	98.4	97.8	91.4
LEAR35	Lockheed	L-1011-500	RB211-524B	213.2	83.9	87.8	101.5
MD81	McDonnell Douglas	MD-80	JT8D-209	62.1	88.9	94.7	92.8
MD9028	McDonnell Douglas	MD-90-30	V2528-D5	70.8	82.6	91.0	91.9
MD11GE	McDonnell Douglas	MD-11	CF6-80C2D1F	263.1	92.8	96.3	103.6
MD11PW	McDonnell Douglas	MD-11	PW4460	263.1	95.8	96.1	104.4

Acknowledgments

This research has been jointly funded by the Centre for Aeronautics, Propulsion, and Power, Faculty of Engineering and Applied Sciences, Cranfield University and Arup.

References

- [1] Civil Aviation Authority, “UK Airport Data February 2019: Table 01 – Size of UK Airports,” , Feb. 2019. URL <https://www.caa.co.uk/data-and-analysis/uk-aviation-market/airports/uk-airport-data/uk-airport-data-2019/february-2019/>.
- [2] Civil Aviation Authority, “UK Airport Data February 2026: Table 01 – Size of UK Airports,” , Feb. 2026. URL <https://www.caa.co.uk/data-and-analysis/uk-aviation-market/airports/uk-airport-data/uk-airport-data-2026/february-2026/>.
- [3] Civil Aviation Authority, “Survey of noise attitudes 2014: Aircraft noise and annoyance, further analysis,” Tech. rep., CAA CAP 2250, 2022.
- [4] European Union Aviation Safety Agency, Eurocontrol, and European Environment Agency, “European Aviation Environmental Report 2019,” , 2020.
- [5] International Air Transport Association, “The Global Commercial Aircraft Fleet,” Tech. rep., International Air Transport Association, 2025.
- [6] U.K. Government, “Government response to the House of Lords Science and Technology Committee report: The neglected pollutants: the effects of artificial light and noise on human health,” Tech. rep., U.K. Government, 12 2023.
- [7] World Health Organization, “Ambient (Outdoor) Air Pollution,” , 2024. URL [https://www.who.int/news-room/fact-sheets/detail/ambient-\(outdoor\)-air-quality-and-health](https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health).
- [8] Jones, K., “ERCD Report 0907: Environmental Noise and Health: A Review,” , 2010.
- [9] United Nations Framework Convention on Climate Change, “The Paris Agreement,” , 2015. URL <https://www.un.org/en/climatechange/paris-agreement>.
- [10] International Air Transport Association, “Our commitment to Fly Net Zero by 2050,” , 2021. URL <https://www.iata.org/en/programs/environment/flynetzero/>.
- [11] International Civil Aviation Organization, “States adopt net-zero 2050 global aspirational goal for international flight operations,” , 2022. URL <https://www.icao.int/Newsroom/Pages/States-adopts-netzero-2050-aspirational-goal-for-international-flight-operations.aspx>.
- [12] European Commission, “Flightpath 2050: Europe’s Vision for Aviation,” , 2011.
- [13] Department for Transport, “Jet Zero strategy: Delivering net zero aviation by 2050,” , 2022.
- [14] Sustainable Aviation, “Net zero carbon road-map: Summary report,” Tech. rep., Sustainable Aviation, 2023.
- [15] Institution of Mechanical Engineers, “Noise Rules ‘Hurt Fuel Efficiency’,” , 2014.
- [16] Lunter, “Overview of the Thirteenth Cycle of the Committee on Aviation Environmental Protection (CAEP/13),” , 2025.
- [17] Luton Rising, “Green Controlled Growth Explanatory Note,” , 2023.
- [18] Sustainable Aviation, “Inter-dependencies between emissions of CO₂, NO_x & noise from aviation: Policy discussion paper 2017 Update,” Tech. rep., Sustainable Aviation, 2017.
- [19] International Civil Aviation Organization, “Report by the second CAEP noise technology independent expert panel - Novel aircraft-noise technology review and medium- and long-term noise reduction goals,” Tech. rep., ICAO Doc 10017, 2014.
- [20] Department for Transport, “Aviation 2050: The Future of UK Aviation – A Consultation,” , 2018. (Cm9714),.
- [21] Graham, W. R., Hall, C. A., and Morales, M. V., “The potential of future aircraft technology for noise and pollutant emissions reduction,” *Transport Policy*, Vol. 34, 2014, pp. 36–51. <https://doi.org/10.1016/j.tranpol.2014.02.017>.

- [22] Stevens, J., Maldonado, A. L., and Proença, A., “High-Level Airport Assessment of Noise and Carbon Emissions Trade-off for Novel Aircraft - A Holistic Approach to Decision Making,” *AIAA Aviation Forum*, American Institute of Aeronautics and Astronautics, 2025. <https://doi.org/10.2514/6.2025-3416>.
- [23] Amargianitakis, D. C., “MONTANA: a high-level noise prediction framework for future novel aircraft,” Ph.D. thesis, University of Southampton, 2024.
- [24] Torija, A. J., Self, R. H., and Flindell, I. H., “A model for the rapid assessment of the impact of aviation noise near airports,” *The Journal of the Acoustical Society of America*, Vol. 141, 2017, pp. 981–995. <https://doi.org/10.1121/1.4976053>.
- [25] Powell, C. A., “Relationship between aircraft noise contour area and noise levels at certification points, NASA-TM-2003-212649,” Tech. rep., NASA, 2003.
- [26] European Environment Agency, *EMEP/EEA air pollutant emission inventory guidebook (EEA Report 06/2023)*, EEA, 2023.
- [27] European Union Aviation Safety Agency, “ICAO aircraft engine emissions databank,” , 2024. URL <https://www.easa.europa.eu/en/domains/environment/icao-aircraft-engine-emissions-databank>.
- [28] Swedish Defence Research Agency, “FOI turboprop emissions database,” , 2021. URL <https://www.foi.se/en/foi/research/aeronautics-and-space-issues/environmental-impact-of-aircraft.html>.
- [29] Rowland, B., “Which part of a flight uses the most fuel?” , 2022. URL <https://www.oag.com/blog/which-part-flight-uses-most-fuel>.
- [30] International Civil Aviation Organization, “ICAO standards and recommended practices: Annex 16, Volume II,” Tech. rep., ICAO, 2022.
- [31] Civil Aviation Authority, “Information on aviation’s environmental impact,” Tech. rep., CAA, 2017.
- [32] EUROCONTROL, “Aircraft Particulate Matter Emission Estimation through all Phases of Flight,” Tech. rep., EUROCONTROL, 2005.
- [33] International Civil Aviation Organization, “Airport Air Quality Manual,” Tech. rep., ICAO Doc 9889, 2020.
- [34] Sustainable Aviation, “The SA Noise Road-map: A Blueprint for Managing Noise from Aviation Sources to 2050,” Tech. rep., Sustainable Aviation, 2013.
- [35] Ryanair Holdings plc, “Ryanair Group Annual Report 2025,” , 2025.
- [36] KLM Royal Dutch Airlines, “KLM Group Chooses Airbus A320neo Family for KLM and Transavia’s European Fleet,” , 2021. URL <https://news.klm.com/klm-group-chooses-airbus-a320neo-family-for-klm-and-transavias-european-fleet/>.
- [37] Caswell, M., “Lufthansa Group Chooses 737-8 MAX for Eurowings Fleet Modernisation,” , 2025. URL <https://www.businessstraveller.com/business-travel/lufthansa-group-chooses-737-8-max-for-eurowings-fleet-modernisation/>.
- [38] Air Cargo Week, “Turkish Airlines to Expand Its Fleet with Boeing Order,” , 2025. URL <https://aircargoweek.com/turkish-airlines-to-expand-its-fleet-with-boeing-order/>.
- [39] Aviation Direct, “EasyJet: Airbus A319 Will Be Phased Out by 2030 in Favor of Larger Neo Models,” , 2025. URL <https://aviation.direct/en/easyjet-airbus-a319-wird-bis-2030-zugunsten-groesserer-neo-modelle-ausgemustert>.
- [40] Jet2, “Jet2 plc Aircraft Order Announcement,” , 2022. URL https://www.jet2.com/news/2022/10/Jet2_plc_Aircraft_Order_Announcement.
- [41] Bujor, M., “United Airlines to Replace Aging Boeing 757 Fleet with Airbus A321XLRs,” , 2026. URL <https://aeronauticsmagazine.com/news/civil-aviation/united-airlines-to-replace-aging-boeing-757-fleet-with-airbus-a321xlr>.
- [42] ZeroAvia, “Our Products,” , 2026. URL <https://zeroavia.com/airframe-manufacturers/>.
- [43] Ostrower, J., “ATR’s ‘massive investment’ targets a 2029 decision for hybrid Evo,” , 2026. URL <https://theaircurrent.com/aircraft-development/atr-2029-evo-decision-hybrid-pw130-strategy/>.
- [44] Embraer Commercial Aviation, “Future Aircraft Concepts,” , 2026. URL <https://embraercommercialaviationsustainability.com/concepts/>.

- [45] Beresnevičius, R., “Airbus 220 Stretch to Enter Service in Early 2030s,” , 2025. URL <https://simpleflying.com/airbus-a220-stretch-enter-service-2030/>.
- [46] Button, K., “Test Time for Hydrogen Fuel Cells,” , 2025. URL <https://aerospaceamerica.aiaa.org/features/test-time-for-hydrogen-fuel-cells/>.
- [47] Airbus, “Airbus advances key technologies for next-generation single-aisle aircraft,” , 2025. URL <https://www.airbus.com/en/newsroom/press-releases/2025-03-airbus-advances-key-technologies-for-next-generation-single-aisle>.
- [48] Garcia, M., “Boeing’s new narrowbody aircraft: What we know so far,” , 2025. URL <https://aerospaceglobalnews.com/news/boeing-new-narrowbody-737-successor/>.
- [49] Cummins, N., “Could Boeing Build a 787X?” , 2020. URL <https://simpleflying.com/boeing-787x/>.
- [50] Stickney, W., “Airbus A350-2000: Stretching the Skies with a New Ultra-Long-Range Widebody,” , 2025. URL <https://boltflight.com/airbus-a350-2000-stretching-the-skies-with-a-new-ultra-long-range-widebody/>.
- [51] Hartley, P., “Confirmed: Boeing 777X To Enter Service in 2027 After 7-Year & \$15 Billion Delay,” , 2026. URL <https://simpleflying.com/boeing-777x-enter-service-2027-7-year-15-billion-delay/>.
- [52] EUROCONTROL, “EUROCONTROL Data Snapshot #53 on Charting the Growth in Market Share of New Generation of Narrow and Wide-Bodies,” , 2025. URL <https://www.eurocontrol.int/publication/eurocontrol-data-snapshot-53-charting-growth-market-share-new-generation-narrow-and>.
- [53] Department for Transport, “Consultation Response on UK Airspace Policy: A framework for balanced decisions on the design and use of airspace,” , 2017. (Cm9520).
- [54] Shukla, A., Prashanth, P., and Speth, R. L., “Impact of Efficiency-Driven Aircraft Technology Improvements on Climate and Air Quality,” *AIAA Aviation Forum*, American Institute of Aeronautics and Astronautics, 2025. <https://doi.org/10.2514/6.2025-3502>.



DSPACE

<https://dspace.org/>

Holistic assessment of the environmental trade-offs of novel aircraft

Stevens, Joy; Maldonado, Ana Luisa; Proenca, Anderson R.

2026-05-26

American Institute of Aeronautics and Astronautics (AIAA)

<https://doi.org/10.2514/6.2026-3321>

Stevens J, Maldonado AL, Proenca A. (2026) Holistic assessment of the environmental trade-offs of novel aircraft. 32nd AIAA/CEAS Aeroacoustics Conference (2026), 26-29 May 2026, Brussels, Belgium, Article number 2026-3321