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# REPRESENTATIVE-IN-CLASS VEHICLES FOR FLEET-LEVEL AVIATION NOISE ANALYSIS

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Global air traffic demand is projected to nearly double by 2035 (7.2 billion passengers) compared to the 3.8 billion passengers in 2016. At such a growth rate, the aviation sector might cause an important detriment of the welfare of those living around airports via a substantial increase in noise. For addressing such a concern, the aviation industry is required to assess a significant number of aviation scenarios, involving different technology platforms and operational procedures, in order to define the strategies that ensure the higher reduction in aircraft noise impact. A common approach to reduce the combinatorial nature of fleet-level studies and enable more flexibility for exploring multiple aviation scenarios, is to simplify the fleet into a number of representative-in-class vehicles that capture the noise performance of the various classes within the fleet. In this paper, a statistical classification process is implemented for reducing the UK commercial fleet into a number of representative-in-class vehicles based on aircraft noise characteristics. The optimal number of representative-in-class aircraft is analysed for three airports in the UK (London Gatwick, Heathrow and Stansted), with significant differences in aircraft movements and fleet composition, on the basis of the accuracy vs. computational time when calculating noise contour areas. Finally, it is discussed the use of these representative-in-class vehicles as baseline models for projecting the reduction in aviation noise impact with future technology implementation.

Keywords: Aviation Noise, Statistical classification, Noise modelling, Aviation noise impact.

## 1. Introduction

With the projected substantial increase in air traffic demand, both the public and policymakers are increasingly concerned about the environmental impacts of the aviation sector [1]. Minimising the community noise exposure, and thus avoid a further deterioration of the quality of life of residents near airports, is one of the main challenges facing commercial aviation [2].

To address such concerns aviation industry is investing a significant effort in developing innovative airframe and engine technologies, designing advanced aircraft procedures, and investigating novel strategies for air traffic management, such as the Heathrow noise respite project [3]. A clever approach for significantly reducing the combinatorial nature of fleet-level studies, and for enabling more flexibility to analyse aviation scenarios with multiple technology, operational and air traffic management options is to reduce the aircraft fleet to a number of representative aircraft categories [4]. For instance, this approach was used by the UK Sustainable Aviation group for assessing the benefit of novel aircraft technologies for reducing the aviation noise exposure in the UK [5].

Some sophisticated methodologies have been developed for modelling average generic vehicles for fleet-level analysis of aviation environmental impacts, such as LeVine et al. [6]. The LeVine et al. [6] methodology allowed a very accurate calculation of noise contours, for most of the US airports tested, when the whole aircraft fleet was replaced with average generic vehicles. However, this methodology was less robust for accurately calculate noise contours in airports with a low volume of operations and with a single aircraft category dominating the fleet. In the UK, a significant number of airports have a reduced volume of operations, and short-medium range aircraft, such as the Airbus A320 family [7], dominates the commercial aircraft fleet.

This paper describes a methodology, based on a statistical process, for the classification of the aircraft fleet and the selection of representative-in-class aircraft. The applicability of this methodology is illustrated and discussed for three UK airports with significant differences in traffic volume and fleet composition: London Gatwick, Heathrow and Stansted airports. Moreover, the use of representative-in-class aircraft as baseline models for analysing and evaluating noise reduction benefits with technological changes within the design space (of baseline models) is discussed.

## 2. Methodology for aircraft classification

### 2.1 Aircraft fleet classification and selection of representative-in-class vehicles

In this paper, the UK commercial aircraft fleet is composed of the 33 aircraft with movements scheduled in the three main London airports (Gatwick, Heathrow and Stansted) as shown in [7]. This fleet was classified into a number of aircraft categories using a hierarchical cluster analysis (HCA). The Ward's method was used for the clustering. This method firstly compute the sum of squared Euclidean distances (SSED) within clusters (between each element and the centroid), and then, aggregate clusters (or elements) which ensure the minimum increase in the within-cluster SSED.

Once the set of clusters (i.e. aircraft categories) was defined, the aircraft with the minimum (Euclidean) distance to the centroid of the corresponding aircraft category was selected as representative-in-class.

$$\min d(a, C) = \sqrt{\sum_{i=1}^{N} (a_i - C_i)^2} \tag{1}$$

where $a$ represents any aircraft belonging to a given category, $C$ is the centroid of that given category, and $N$ is the set of independent variables used for the HCA.

### 2.2 Variables for HCA

The aircraft classification and selection of representative-in-class vehicles was based on aircraft noise emission (at a vehicle-level). The aircraft noise emission is measured using Sound Exposure Level (SEL) contours. The SEL contour areas from 70 dBA to 100 dBA (in 5 dB intervals) were used as independent variables for the HCA. These SEL were selected as representative of the maximum sound-levels when the aircraft is taking-off at maximum power, and of the sound-levels further away from the runway (after the power cut-off point) when the aircraft is flying with a reduced power (see Fig. 1).

The noise contours (and noise contour areas) were computed with the Integrated Noise Model (INM) [8] for arrival and departure operations, assuming a straight-in/straight-out trajectory. For departure operations, noise contour areas with the whole set of "Standard" flight procedures [9] were computed for each aircraft tested. The final departure noise contour areas assigned to each aircraft were the average values between the computed set of noise contour areas with "Standard" flight procedures.

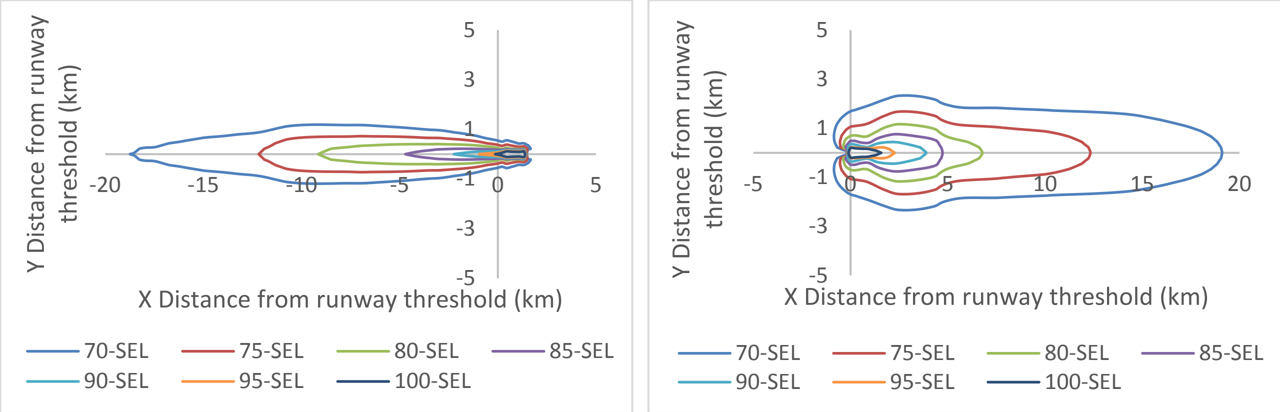


Figure 1: SEL contours of the Airbus A320-232 aircraft at arrivals (left) and departure (right).

### 2.3 Data analysis

To analyse the applicability of the aircraft classification method described for aviation noise studies, fleet noise contours were calculated with the aircraft fleet published in 2015 by the UK Civil Aviation Authority (CAA) for the London airports: Gatwick, Heathrow and Stansted [7]. As shown in Table 1, these three airports differs significantly in terms of air traffic movements and fleet composition.

Table 1: Aircraft fleet (movements/day in year 2015) for Gatwick, Heathrow and Stansted airports. In brackets, it is shown the percentage of movements.

| Aircraft type | Gatwick | Heathrow | Stansted |
|---|---|---|---|
| Propeller | 9.3 (1%) | 0.2 (0%) | 23.4 (5%) |
| Narrow-body | 793 (91%) | 854.6 (63%) | 449.8 (91%) |
| Wide-body (2 engines) | 51.9 (6%) | 359.3 (27%) | 12.5 (3%) |
| Wide-body (3/4 engines) | 13.5 (2%) | 140.2 (10%) | 9.2 (2%) |
| Overall Movements | 867.7 | 1354.3 | 494.9 |

The metric used for measuring the noise exposure at a fleet-level was the $L_{Aeq,16h}$, which is the metric used in the UK for assessing noise impacts around airports [10]. The $L_{Aeq,16h}$ contour areas from 51 dBA to 66 dBA (in 3 dB intervals) were computed in order to encompass sound-levels representing from low annoying to highly annoying conditions.

For each airport, fleet noise contour areas where computed with the whole aircraft fleet (i.e. 33 aircraft), and also replacing the fleet with a number (from 1 to 30) of representative-in-class vehicles, as selected using the methodology described in this paper. The changes in accuracy (for computing noise contour areas) and computation time (i.e. defined as the time used by INM for calculating noise contours) with the variation in the number of representative-in-class aircraft were explored in order to define an optimal simplification of the aircraft fleet for each airport evaluated.

## 3. Noise contours calculations: Accuracy vs. computational time

The relative error of the calculation of noise contours when the whole aircraft fleet is replace with a number, $n \in [1,2,\ldots,N]$ for $N = 30$, of representative-in-class aircraft, and the associated computational time is shown in Fig. 2, for the fleet of the three airports under study: Gatwick (top), Heathrow (middle) and Stansted (bottom).

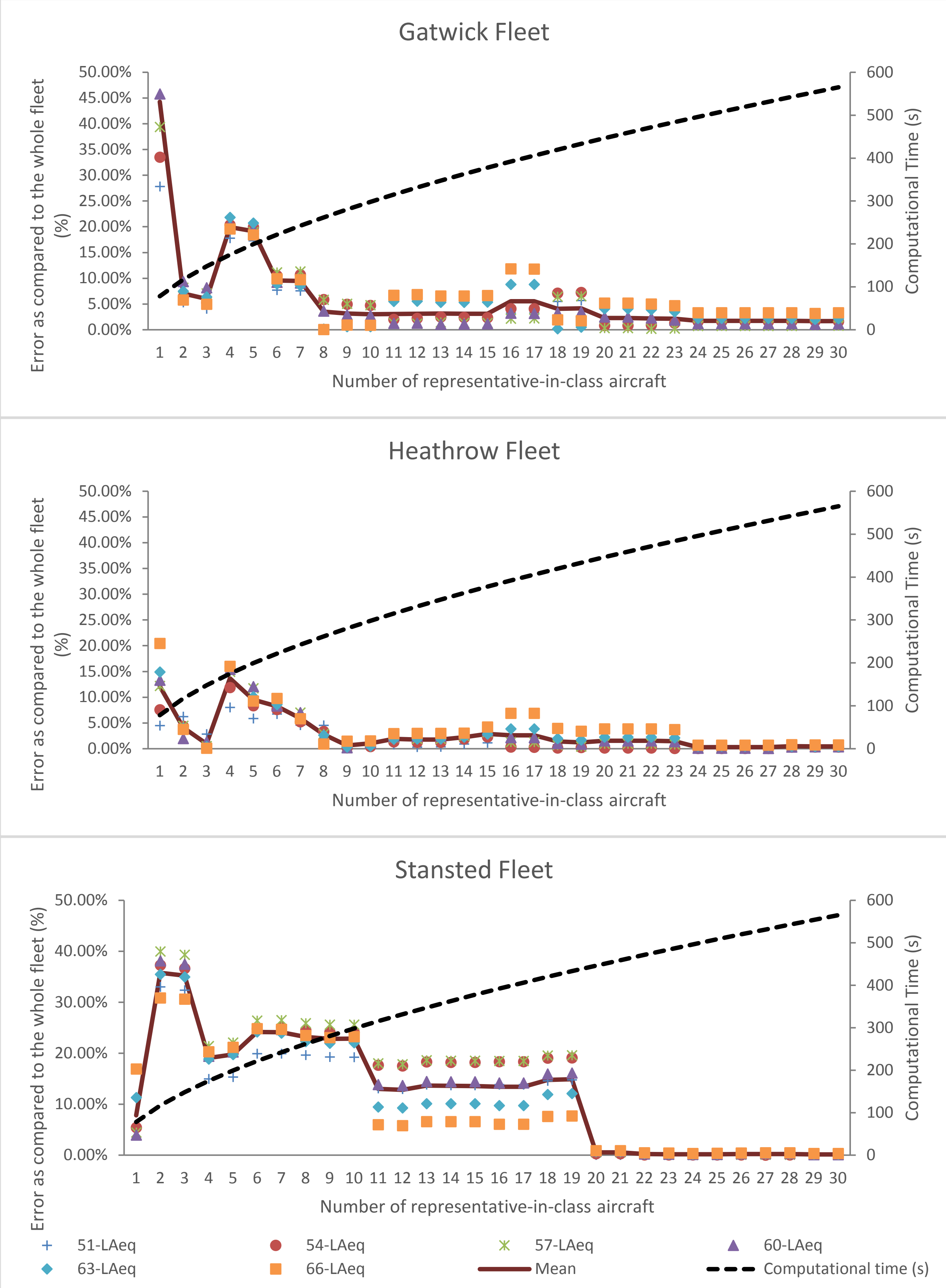


Figure 2: Relative error of the calculation of noise contour areas when a number of representative-in-class ($n = [1, \ldots, 30]$) replaces the whole aircraft fleet aircraft and the associated computational time, for the Gatwick (top), Heathrow (middle) and Stansted (bottom) aircraft fleet in 2015.

As shown in Fig. 2, in general, the relative error is smaller for the airport with the aircraft movements more evenly distributed across the different aircraft types, i.e. Heathrow (see Fig. 2 – middle and Table 1). For the fleets of Gatwick and Heathrow airports (Fig. 2 top and middle respectively) a significant reduction in relative error is observed the 3 representative-in-class vehicles are used for computing noise contour areas. However, this is a 'local minima', and when 4 and 5 representative-in-class vehicles are used, the relative error notably increases. This is an indication that the clustering process (based on HCA as described above) has not reached an optimal solution, and therefore, some of the clusters built are not robust enough in terms of internal homogeneity. Only with at least 8 representative-in-class vehicles the relative error becomes stable between 0-5%. The average time for computing noise contours with 8 representative-in-class vehicles is 261.9 s, 56% faster than the computation with the whole aircraft fleet (597.2 s).

A special case is observed for the aircraft fleet of Stansted airport (Fig.2 – bottom). In Gatwick airport (in year 2015), the 70% of aircraft movements corresponded to Boeing 737-800 aircraft. As shown in Fig. 2 (bottom), only when the Boeing 737-800 aircraft is selected as a representative-in-class vehicle (iteration 20), the relative error is significantly reduced to a value between 0-1%. For this specific airport, if the noise contour areas are calculated with the 2 most utilised aircraft, i.e. Boeing 737-800 and Airbus A319 aircraft (representing 82% of movements), a relative error of about 5% is observed.

## 4. Baseline models for technology-infused aircraft analyses

To select baseline vehicles for parametric studies evaluating the noise benefits of different technology improvements, a clustering process (HCA) and representative-in-class selection as described above was carried out: (1) removing all the aircraft out-of-production, and (2) including a number of physical variables linked to the environmental performance of aircraft [4] as independent variables for the clustering process. These physical variables are: (i) Number of engines (NoE); (ii) Bypass Ratio (BPR): ratio of the air mass flow through the bypass ducts to the air mass flow through the engine core of a gas turbine engine; (iii) Overall Pressure Ratio (OPR): ratio of the mean total pressure at the last compressor discharge plane of the compressor to the mean total pressure at the compressor entry plane when the engine is at take-off thrust conditions; (iv) Rated output ($F_{00}$): the maximum thrust available for take-off [11]; (v) Average Departure Weight (DW): average aircraft weight at departure conditions between all the "Standard" flight profiles published in the ANP database [9]; (vi) Landing Weight (LW): aircraft weight at landing conditions.

Table 2: Aircraft selected as baseline models for technology-infused studies, on the basis of physical characteristics and noise emission.

| Aircraft physical characteristics | CRJ-900 | 737–700 | A330-343 | A380-841 |
|---|---|---|---|---|
| Engine | BR710 | CFM56-7B24 | TRENT-772B | TRENT-970 |
| Number of Engines (NoE) | 2 | 2 | 2 | 4 |
| Bypass Ratio (BPR) | 4.20 | 5.20 | 5.00 | 7.5 |
| Overall Pressure Ratio (OPR) | 24.31 | 25.78 | 36.30 | 38.97 |
| Rated output ($F_{00}$) | 65.61 | 107.65 | 320.30 | 334.70 |
| Average Departure Weight (DW), tonnes | 34.89 | 62.39 | 193.41 | 465.75 |
| Landing Weight (LW), tonnes | 30.74 | 52.25 | 168.28 | 362.49 |

Four aircraft categories, and the corresponding 4 representative-in-class aircraft were found (Table 2). These findings are consistent with Torija et al. [4]. The 4 aircraft identified are: Bombardier CRJ-900 (regional jet), Boeing 737-700 (short/medium range with two engines), Airbus A330-343 (long range with two engines), and Airbus A380-840 (long range with 4 engines).

Once the representative baseline models are defined, aircraft noise level variations arising from technological changes can be computed with the framework developed by Synodinos et al. [12].

Synodinos et al. [12] defines the aircraft sound power level consequence of technology changes as

$$L_w = 10\log_{10}\left[\sum_{s=1}^{S} 10^{\left(\left(L_{w0,s}+\Delta L_{w,s}\right)/_{10}\right)}\right] \tag{2}$$

where $L_{w0,s}$ is the sound power level of each individual source ($s \in [1,2,\dots,S]$) of the baseline aircraft, and $\Delta L_{w,s}$ is the variation in sound power level of each individual source, estimated using publicly available semi-empirical methods existing for noise prediction of individual aircraft sources (e.g. Jet, Fan, Airframe, etc.).

The resulting instantaneous sound pressure level of the aircraft flying-over is calculated as

$$L_p(t) = L_w + 10\log_{10}\left(\frac{D(t)}{R^2(t)}\right) + C \tag{3}$$

where $D(t)$ and $R(t)$ is a normalised directivity factor and the distance (between aircraft and receiver) corresponding to each time increment of the aircraft flyover, and $C$ is a constant related to ambient conditions. The Sound Exposure Level (SEL) is computed integrating the instantaneous $L_p$ over the time interval $[t_1, t_2]$, which corresponds to the flyover period where the instantaneous $L_p$ is within $L_{A,max} - 10$ dB

$$\mathrm{SEL} = 10\log_{10}\int_{t_1}^{t_2} 10^{\left(L_p(t)/_{10}\right)} dt \tag{4}$$

Further details about the framework described above can be found at Synodinos et al. [12]. The resulting noise outputs can be used by airport noise models (such as Torija et al. [13]) for assessing the noise benefits of novel aircraft technologies at a fleet-level. An illustrative example is shown in Fig. 3, where the change in 57-$L_{Aeq,16h}$ noise contour area in the UK for the period 2015-2050 is estimated for three scenarios: (i) assuming that there is no introduction of novel aircraft technologies, (ii) assuming that all aircraft manufactured before 2007 are retired, and (iii) assuming a new generation of aircraft is introduced in 2030 with the noise emission reduced to meet ICAO-CAEP-IEP2 targets [14]. The air traffic demand forecast as projected by the Department for Transport of the UK [15] was used for this analysis.

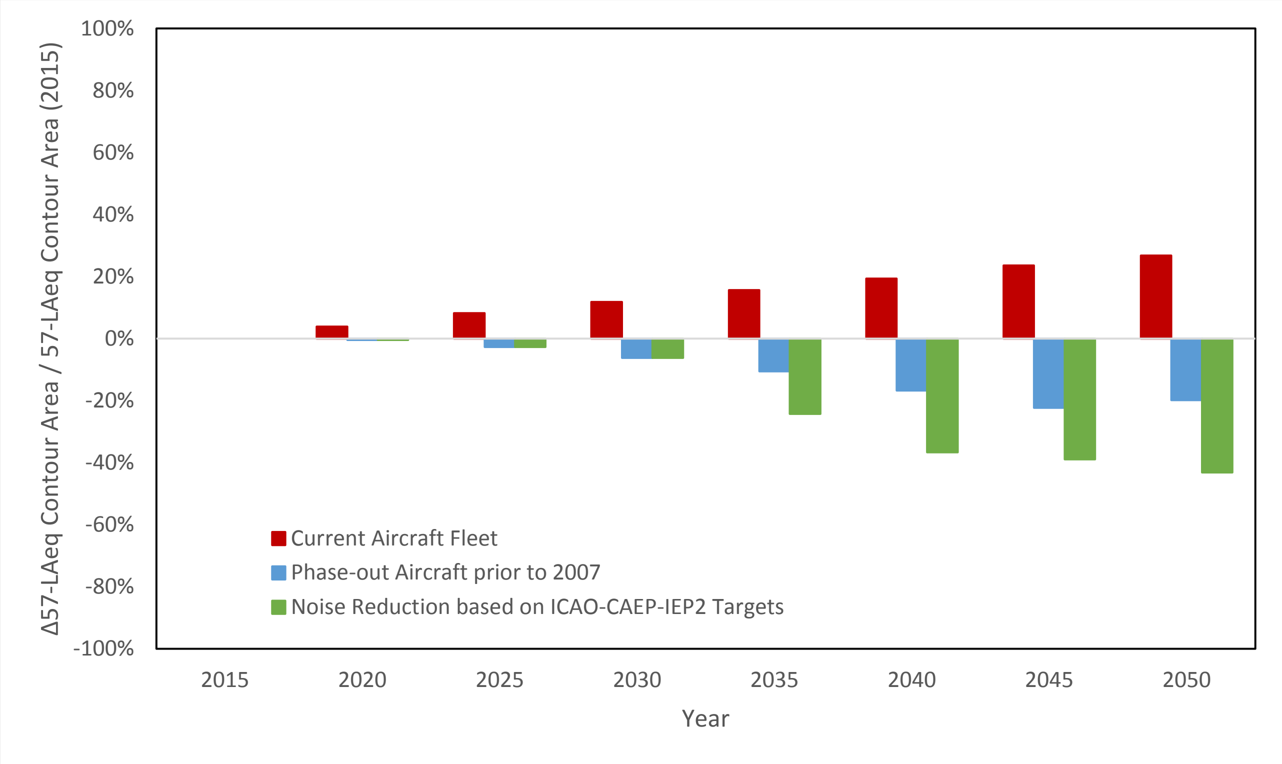


Figure 3: Change in 57-$L_{Aeq,16h}$ noise contour area in the UK for the period 2015-2050, without novel aircraft technologies (red bars), retiring all aircraft produced before 2007 (blue bars) and introducing new aircraft (in 2030) meeting ICAO-CAEP-IEP2 targets [14].

## 5. Conclusions

This paper describes a statistical process for classifying the aircraft fleet into categories capturing the different noise emission characteristics, and then selecting representative-in-class vehicles. Regardless the overall number of movements and the fleet composition, the statistical classification and selection process described in this paper allows a significant reduction in the computational time with a relative minor decrease in accuracy. A 56% reduction in the computational time with an average relative error smaller than 5% is found for Gatwick and Heathrow airports fleet when the whole fleet is replaced with 8 representative-in-class aircraft. Only when a single aircraft type significantly dominates the aircraft fleet (above 70% of overall movements), the described statistical process does not converge until this aircraft type is selected as representative-in-class.

On the basis of aircraft physical characteristics and noise emissions, 4 baseline models are defined for aircraft technology-infused studies. Parametric studies can be performed for estimating the variation in noise level due to technological changes within the design space of the baseline model. Adding the variations in noise levels to the noise level of the baseline model allows the assessment of the performance of different technology improvements for minimizing aviation noise exposure.

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