# On the $CO_2$ and noise emissions forecast in future aviation scenarios in the UK

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## ABSTRACT

Aircraft operations have a significant impact on local air quality, climate change, fuel consumption and noise around airports. In order to reach emission targets set by aviation agencies (e.g. ACARE), to reduce environmental impact and to ensure a sustainable future of the sector, the aviation industry is continuously investing in research and development of technologies for reducing $CO_2$, noise and other emissions. However, different technology platforms might have different effects in terms of $CO_2$ and noise emissions reduction, e.g. Counter-Rotating Open-Rotors (CROR) are estimated to achieve higher reduction in fuel consumption but lower noise reduction than future turbofan designs. On the basis of fuel-burn and noise reduction trend projections found in the relevant literature, this work is aimed at addressing a comparative analysis between the reduction in noise and $CO_2$ emissions of imminent and future generations that will replace current aircraft. Based on the concept of airport noise efficiency, and for easily performing $CO_2$ versus noise interdependencies analyses, a metric for assessing aircraft noise efficiency is defined. Moreover, $CO_2$ and noise emissions are forecast for a number of future aviation scenarios in the UK, on the basis of different aviation growth rates and aircraft technologies.

Keywords: Aviation Noise, CO2, Forecast I-INCE Classification of Subjects Number(s): 13.1, 52.2, 68.3.

## 1. INTRODUCTION

While it is recognized that air transportation brings significant economic and social benefits (1), it also leads to externalities in terms of climate change, noise and local air quality impacts, and consequently affect the health and quality of life of citizens (2). Aviation industry is striving to reduce its environmental footprint in the short- and long-term, and also to reduce the cost associated to fuel consumption (3). Thus, engine and aircraft manufactures are investing a significant effort in the development of ongoing research programs for enhancing fuel-burn efficiency, and reducing the emission of noise and air pollutants (such as $CO_2$ and NOx). However, much of this improvement might be offset by the huge increase in air traffic demand as expected by different agencies (4, 5).

At a national or international level, the aviation sector is mainly focused on minimising the emission of $CO_2$ (6), which has been widely recognized as the dominant greenhouse gas responsible for global warming (7). Meanwhile, at a local level, the aviation sector is mainly driven by the reduction in the emission of noise and local air quality pollutants, e.g. NOx (6). The difficulty arises when the goal is addressing simultaneously the reduction of the three types of pollutants. In fact, the development of technologies for achieving an improvement in the minimisation of one pollutant can lead to negative effects in the emission of the others. This paper pays special attention to the case of Counter-Rotated Open-Rotors (CROR), which are intended to replace the current short-haul aircraft types. Compared to future turbofans, CROR have the potential to be more efficient in terms of fuel-burn, but at the expense of achieving a lower reduction in the noise emitted (6).

In this paper, noise and $CO_2$ emissions are forecast for a number of potential future scenarios in the UK, i.e. three air traffic demand projections as suggested by the Department for Transport in the

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UK, DfT (5), with and without the introduction of CROR. Regarding the aircraft technology improvements, the noise reduction rates as assumed by the ICAO CAEP IEP2 (8) and the fuel-burn reduction rates as assumed by Sustainable Aviation (SA) in the development of the $CO_2$ roadmap for the UK (9) are used for the purpose of this paper. For each scenario, CO2 and noise forecasts are compared and discussed. Moreover, this paper is aimed at addressing a comparative analysis (for each aircraft category) between the reduction in noise and $CO_2$ emission of imminent and future generations (hereafter called generation G1 and G2 respectively) that will replace current aircraft types (hereafter called generation G0). This comparative analysis is based on the value of both fuel-burn efficiency (measured as fuel-burn per passenger-kilometer) and aircraft noise efficiency, defined in this paper as the sound intensity (watts/$m^2$) emitted per passenger-kilometer. From this comparative analysis, the contribution of each aircraft category to the total $CO_2$ and noise emitted by the whole fleet in the UK aviation sector, for the current and future scenarios, is evaluated and discussed.

## 2. METHODOLOGY FOR AVIATION NOISE FORECAST

The aviation noise forecast is calculated on the basis of the current aircraft fleet in the UK, the growth in air traffic demand, the rate of penetration into the fleet of aircraft generations G1 and G2, and the sound-levels of individual aircraft of generations G0, G1 and G2.

### 2.1 Air Traffic Movement (ATM) Projection Scenarios

As indicated above, the noise forecast is calculated using the aviation growth projections reported by the DfT for the UK (5), under the Low, Central and High (constrained) scenarios (Table 1). It should be noted that DfT assumes the same growth rate for all the aircraft categories within the fleet. The DfT-Central forecast assumes the aircraft movements to grow annually by varying amounts between 0.8% and 2.0%, resulting in an overall growth of 89% by 2050. The DfT-Low forecast assumes no increase in aircraft movements in the 2010-2015 period and then an annual increase in traffic demand between 0.7% and 1.9%, resulting in an overall growth of 53% by 2050. The constrained DfT-High forecast assumes that no new runways will be built in the UK. In this constrained forecast, the air traffic is projected to grow annually between 1.6% and 2.6%, with an overall growth of 89% by 2040 (between 2040 and 2050 no increase is expected).

Table 1 – ATM growth rates (p.a.) as projected by DfT (ref) for the Low, Central and High (constrained) scenarios

| ATM projection | Period | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 2011 - 2015 | 2016 - 2020 | 2021 - 2025 | 2026 - 2030 | 2031 - 2035 | 2036 - 2040 | 2041 - 2045 | 2046 - 2050 |
| DfT-Low | 0.0% | 1.0% | 1.8% | 0.9% | 0.8% | 1.9% | 1.4% | 0.7% |
| DfT-Central | 0.8% | 1.8% | 2.0% | 1.6% | 1.7% | 1.6% | 1.9% | 1.3% |
| DfT-High (constrained) | 1.9% | 2.6% | 1.6% | 2.1% | 2.5% | 2.2% | - | - |

### 2.2 Sound-levels of Aircraft Generations G0, G1 and G2

Based on aircraft categorisation as proposed by (8), the aircraft fleet in the UK is classified into 4 categories: Regional Jets (RJ), Small/Medium Range Twin (SMRT), Long Range Twin (LRT) and Long Range Quad (LRQ). For each of these categories, a reference aircraft of the current generation G0 ('year 2000 generation') is selected: (i) Bombardier CRJ-900 for RJ, (ii) Boeing 737-800 for SMRT, (iii) Airbus A330-343 for LRT and (iv) Boeing 747-400 for LRQ.

Three aircraft generations are considered: generation G0 (current aircraft in service), generation G1 ('imminent' aircraft generation entering service over the next few years, which incorporate novel technology already developed) and generation G2 (future aircraft generation incorporating novel noise-reducing airframe and engine designs still under research and development). For calculating the number of aircraft corresponding to each generation ($N_{G0}$, $N_{G1}$ and $N_{G2}$), a linear transition from G0 to G1 and from G1 to G2 is assumed, based on the data showed in Table 2.

Table 2 – Entry into service (EIS) for aircraft of imminent (G1) and future (G2) generations as suggested by (10). In brackets the length of the transition period

| Aircraft category | $EIS_{G1}$ | $EIS_{G2}$ |
|---|---|---|
| RJ | 2015 (30) | 2040 (20) |
| SMRT | 2015 (30) | 2025 (25) |
| SMRT (CROR) | 2015 (30) | 2025 (25) |
| LRT | 2014 (26) | 2040 (20) |
| LRQ | 2007 (20) | 2040 (20) |

The current aircraft fleet in service in the UK and the number of movements for each individual aircraft were obtained from (10). The sound-levels in EPNdB for each individual aircraft of generation G0 ( $L_{G0}$ ) at each certification point were found in the NoisedB database (http://noisedb.stac.aviation-civile.gouv.fr/).

The aviation noise is forecast considering the noise reduction due to technology improvements in generations G1 and G2. For generations G1 and G2, a 'representative' sound-level in EPNdB was estimated for each aircraft category and at each certification point. The sound-levels for generation G1 ($L_{G1}$) were obtained from (10). For generation G2, the sound-levels ($L_{G2}$) (for each certification point) were estimated using the data showed in Tables 2 and 3, as follows:

$$L_{G2} = L_{G1} - \left(NR \cdot (EIS_{G2} - EIS_{G1})\right) \quad (1)$$

As indicated above, the noise reductions suggested by ICAO CAEP IEP2 (8), with and without the introduction of CROR replacing current SMRT aircraft, were used for estimating the $L_{G2}$. It should be noted that the NR of ICAO CAEP IEP2 scenario (Table 3) were derived from the comparison between $L_{G1}$ (at $EIS_{G1}$) and the target noise level, i.e. current '2000 noise level' – noise reduction in EPNdB suggested in (9) by 2030 (long-term goal date in (9)).

Table 3 – Noise reduction rates p.a. (NR) per operation at each certification point due to noise reduction technologies as projected by ICAO CAEP IEP2 (8)

| Aircraft category | Lateral | Flyover | Approach |
|---|---|---|---|
| RJ | 0.25 | 0.05 | 0.23 |
| SMRT | 0.51 | 0.54 | 0.33 |
| SMRT (CROR) | 0.00 | 0.21 | 0.11 |
| LRT | 0.40 | 0.03 | 0.22 |
| LRQ | 0.19 | 0.15 | 0.02 |

For each aircraft of each generation, the total sound-level generated by both the departure and approach operations is defined as

$$L_{LTO} = 10 \cdot \log_{10}\left[10^{\left(\left((L_{lat}+L_{fly})/2\right)/10\right)} + 10^{\left((L_{app}-9)/10\right)}\right] \quad (2)$$

where $L_{lat}$, $L_{fly}$ and $L_{app}$ is the sound-level at the lateral, flyover and approach certification points.

### 2.3 Estimation of Aviation Noise Metric (Sound Intensity)

Before calculating the sound intensity emitted by each aircraft within the fleet for the current generation G0, and generations G1 and G2, the total sound exposure level generated by each individual aircraft in both departure and approach operations ($\mathrm{SEL_{LTO}}$) was estimated from a series of linear least square regression analyses for the set of current G0 aircraft using the sound-level in EPNdB ($\mathrm{L_{LTO}}$) as dependent variable.

For each individual aircraft $i$ of each generation (G0, G1 and G2), let us define the sound intensity generated by each individual aircraft in both departure and approach operations as

$$\mathrm{I}_{\mathrm{LTO},i} = \frac{\mathrm{P}_0^2 \cdot 10^{(\mathrm{SEL}_{\mathrm{LTO},i}/10)}}{\mathrm{Z}} \tag{3}$$

where $\mathrm{P}_0$ is the reference sound pressure ($2 \cdot 10^{-5}$ Pa) and $\mathrm{Z}$ is the acoustic impedance ($400\,\mathrm{N} \cdot \mathrm{s/m^3}$).

For each aircraft category $j$ of each generation, composed of $n$ individual aircraft $i$, the sound intensity generated by the set of individual aircraft within the aircraft category (in both departure and approach operations) is defined as

$$\mathrm{I}_{\mathrm{LTO},j} = \sum_i^n \mathrm{N}_{\mathrm{G0},i} \cdot \mathrm{I}_{\mathrm{LTO,G0},i} + \sum_i^n \mathrm{N}_{\mathrm{G1},i} \cdot \mathrm{I}_{\mathrm{LTO,G1},i} + \sum_i^n \mathrm{N}_{\mathrm{G2},i} \cdot \mathrm{I}_{\mathrm{LTO,G2},i} \tag{4}$$

where $\mathrm{N}_{\mathrm{G0},i}$, $\mathrm{N}_{\mathrm{G1},i}$ and $\mathrm{N}_{\mathrm{G2},i}$ are the number of movements for each individual aircraft $i$ of generations G0, G1 and G2 respectively, and $\mathrm{I}_{\mathrm{LTO,G0},i}$, $\mathrm{I}_{\mathrm{LTO,G0},i}$ and $\mathrm{I}_{\mathrm{LTO,G0},i}$ is the sound intensity of each individual aircraft $i$ of generations G0, G1 and G2 respectively.

The sound intensity corresponding to the whole aircraft fleet ($\mathrm{I_{LTO,fleet}}$) is obtained as the sum of the sound intensity of the four aircraft categories considered. The $\mathrm{I_{LTO,fleet}}$ is calculated for each year $m$, between years 2010-2050. The relative change in sound intensity at a given year $m$ ($\Delta \mathrm{I}_{rel,m}$) with the increase of aviation growth and the introduction of quieter future aircraft is expressed as

$$\Delta \mathrm{I}_{rel,m} = \frac{\left(\mathrm{I}_{\mathrm{LTO,fleet},m} - \mathrm{I}_{\mathrm{LTO,fleet.2010}}\right)}{\mathrm{I}_{\mathrm{LTO,fleet.2010}}} \tag{5}$$

where $\mathrm{I}_{\mathrm{LTO,fleet},m}$ and $\mathrm{I}_{\mathrm{LTO,fleet.2010}}$ is the sound intensity corresponding to the whole aircraft fleet at year $m$ and year 2010 respectively.

### 2.4 Aircraft Noise Efficiency

Based on the concept of airport noise efficiency, and for enabling fair $CO_2$ versus noise interdependencies analysis, an aircraft noise efficiency (ANE) metric is defined as

$$\mathrm{ANE} = \frac{\mathrm{I_{LTO}}}{\mathrm{Pax} \cdot \mathrm{Range}} \ (\mathrm{watts/m^2 \cdot pax \cdot km}) \tag{6}$$

where Pax and Range are the number of passengers carried by and the maximum range (in km) of an individual aircraft. The Pax and Range values were obtained from (http://www.airliners.net/). It should be noted that, because of the lack of trusted data, the Pax and Range values for each aircraft category of generations G1 and G2 was assumed as the same as the Pax and Range values of the reference aircraft of the corresponding aircraft category of generation G0.

## 3. METHODOLOGY FOR AVIATION $CO_2$ FORECAST

### 3.1 Revenue Passenger-Km (RPK) Projection and Fuel-Burn Reduction Scenarios

The $CO_2$ emitted by the aviation sector is intrinsically linked to the fuel-burn value of the aircraft fleet. In this paper, based on the methodology used in (9), the aviation CO2 forecasts are calculated on the basis of the fuel-burn shared between aircraft categories, the projected change in revenue passenger-kilometer (RPK), i.e. the number of revenue-paying passengers carried by the aircraft fleet multiplied by the distance travelled, and the replacement of current aircraft types with more fuel-burn efficient aircraft.

For the sake of comparability with the noise forecast, the same scenarios projected by the DfT, i.e. Low, Central and High (constrained), are used for the calculation of the $CO_2$ forecast (Table 4). The DfT-Low, DfT-Central and DfT-High (constrained) scenarios assume annual RPK growth rates between 1.1% - 2.0%, 1.9% - 2.5%, and 1.0% - 3.2% respectively. The resulting overall increase in RPK projected by 2050 is 77% (DfT-Low) and 131% (DfT-Central and High). It should be noted that, in DfT-High scenario, the maximum RPK is assumed to take place in 2045, with no increase between years 2046-2050.

Table 4 – RPK growth rates (p.a.) as projected by DfT (5) for the Low, Central and High (contrained) scenarios

| RPK projection | Period | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 2011 - 2015 | 2016 - 2020 | 2021 - 2025 | 2026 - 2030 | 2031 - 2035 | 2036 - 2040 | 2041 - 2045 | 2046 - 2050 |
| DfT-Low | 1.5% | 1.7% | 2.0% | 1.7% | 1.0% | 1.2% | 1.2% | 1.1% |
| DfT-Central | 2.1% | 2.5% | 2.3% | 2.0% | 1.7% | 2.1% | 2.4% | 1.9% |
| DfT-High (constrained) | 2.7% | 3.2% | 2.3% | 2.2% | 2.6% | 3.0% | 1.0% | - |

For the elaboration of the $CO_2$ roadmap in the UK, in (9) the RJ aircraft were considered within the SMRT category, and thus the data about fuel-burn share and fuel-burn reduction rates are only provided for SMRT, LRT and LRQ categories. For this reason, in the calculation of the CO2 forecast, it should be noted that the SMRT category includes both RJ and SMRT aircraft. As for the noise forecast, three aircraft generations are considered, i.e. G0, G1 and G2. For each aircraft category, and considering the introduction of CROR as replacement for SMRT types, the fuel-burn reduction rates due to technology improvements as suggested by (9) for the generations G1 and G2 (relative to their predecessor generation, i.e. G0 and G1 respectively) were used for calculating the $CO_2$ forecast (Table 5).

Table 5 – Fuel-burn reduction (%) for G1 and G2 aircraft generations relative to their predecessor aircraft types (G0 and G1 respectively), as estimated in (9). In brackets it is shown the fuel-burn reduction (%) for generation G2 relative to generation G0.

| Aircraft category | G1 | G2 |
|---|---|---|
| SMRT | 13% | 13% (24%) |
| SMRT (CROR) | 13% | 25% (35%) |
| LRT | 20% | 38% (50%) |
| LRQ | 17% | 45% (54%) |

### 3.2 Estimation of Aviation $CO_2$

Assuming that the $CO_2$ emitted by the whole aircraft fleet changes proportionally to the change in RPK, then for any year $m$, from 2011 to 2050

$$\mathrm{CO}_{2,\mathrm{G0},m} = \mathrm{CO}_{2,\mathrm{G0},m-1} \cdot (1 + \Delta\mathrm{RPK}_m) \tag{7}$$

where $\mathrm{CO}_{2,\mathrm{G0},m}$ is the $CO_2$ emitted by the whole aircraft fleet, composed only of current types, in the year $m$, and $\Delta\mathrm{RPK}_m$ is the RPK growth rate p.a. in the year $m$. Note that the $\mathrm{CO}_{2,\mathrm{G0}}$ at year 2010 (32.3 Mt) was obtained from (5).

Considering the introduction of technology improvements, the $CO_2$ emitted by the whole aircraft fleet, with the replacement of current types by more fuel-efficient aircraft of generations G1 and G2 in any year $m$ from 2010 to 2050 ($\mathrm{CO}_{2,\mathrm{TI},m}$), is calculated as follows

$$\mathrm{CO}_{2,\mathrm{TI},m} = \left(\mathrm{CO}_{2,\mathrm{G0},m} \cdot \mathrm{FB}_{\mathrm{F,G1},m}\right) \cdot \mathrm{FB}_{\mathrm{F,G2},m} \tag{8}$$

where $\mathrm{FB}_{\mathrm{F,G1},m}$ and $\mathrm{FB}_{\mathrm{F,G2},m}$ are fuel-burn factors for generations G1 and G2 respectively. For either aircraft generation $g$ (G1 or G2), the fuel-burn factor $\mathrm{FB}_{\mathrm{F,G}g,m}$ can be obtained as

$$\mathrm{FB}_{\mathrm{F,G}g,m} = 1 - \left(\mathrm{FB}_{\mathrm{S,SMRT}} \cdot \mathrm{FB}_{\mathrm{R,G}g,\mathrm{SMRT},m} + \mathrm{FB}_{\mathrm{S,LRT}} \cdot \mathrm{FB}_{\mathrm{R,G}g,\mathrm{LRT},m} + \mathrm{FB}_{\mathrm{S,LRQ}} \cdot \mathrm{FB}_{\mathrm{R,G}g,\mathrm{LRQ},m}\right) \tag{9}$$

where $\mathrm{FB}_{\mathrm{S,SMRT}}$, $\mathrm{FB}_{\mathrm{S,LRT}}$ and $\mathrm{FB}_{\mathrm{S,LRQ}}$ is the share of fuel-burn between the SMRT, LRT and LRQ categories, i.e. 31%, 42% and 27% respectively as found in (9); and $\mathrm{FB}_{\mathrm{R,G}g,\mathrm{SMRT},m}$, $\mathrm{FB}_{\mathrm{R,G}g,\mathrm{LRT},m}$ and $\mathrm{FB}_{\mathrm{R,G}g,\mathrm{LRQ},m}$ is the fuel-burn reduction for SMRT, LRT and LRQ of either generation G1 or G2. It must be noted that only flights departing from the UK airports were considered for the purpose of the $CO_2$ forecast. For any generation $g$, any aircraft category $j$, and any year $m$

$$\mathrm{FB}_{\mathrm{R,G}g,j,m} = \begin{cases} 0 & \text{if} \quad m \leq \mathrm{EIS}_{\mathrm{G}g,j} \\ \dfrac{\mathrm{FB}_{\mathrm{r,G}g,j} \cdot \left(m - \mathrm{EIS}_{\mathrm{G}g,j}\right)}{\mathrm{TP}_{\mathrm{G}g,j}} & \text{if} \quad \mathrm{EIS}_{\mathrm{G}g,j} < m \leq \left(\mathrm{EIS}_{\mathrm{G}g,j} + \mathrm{TP}_{\mathrm{G}g,j}\right) \\ \mathrm{FB}_{\mathrm{r,G}g,j} & \text{if} \quad m > \left(\mathrm{EIS}_{\mathrm{G}g,j} + \mathrm{TP}_{\mathrm{G}g,j}\right) \end{cases} \tag{10}$$

with $\mathrm{EIS}_{\mathrm{G}g,j}$ and $\mathrm{TP}_{\mathrm{G}g,j}$ as the entry into service and the length of the transition period for the generation $g$ and the aircraft category $j$, as shown in Table 2; and $\mathrm{FB}_{\mathrm{r,G}g,j}$ as the fuel-burn reduction rate for the generation $g$ and the aircraft category $j$, as shown in Table 5.

As for the noise forecast, the relative change in $CO_2$ emitted in a given year $m$ ($\Delta\mathrm{CO}_{2,rel,m}$) with the increase of aviation growth and the introduction of more fuel-burn efficient future aircraft is expressed as

$$\Delta\mathrm{CO}_{2,rel,m} = \frac{\left(\mathrm{CO}_{2,\mathrm{TI},m} - \mathrm{CO}_{2,\mathrm{TI},2010}\right)}{\mathrm{CO}_{2,\mathrm{TI},2010}} \tag{11}$$

where $\mathrm{CO}_{2,\mathrm{TI},m}$ and $\mathrm{CO}_{2,\mathrm{TI},2010}$ is the $CO_2$ emitted by the whole aircraft fleet at year $m$ and year 2010 respectively.

## 4. RESULTS

### 4.1 Noise and $CO_2$ Forecast

Figure 1 shows the change (relative to year 2010) in sound intensity (left) and $CO_2$ (right) for the DfT air traffic projection under the Low (top), Central (middle) and High (bottom) scenarios, between year 2010 and 2050. Assuming an aircraft fleet composed only of current types – plus LRQ aircraft of generation G1 which entered into service in 2007 – (blue lines), it is estimated by 2050 a relative increase in sound intensity between 39-73% (DfT-Low and Central/High respectively) and a relative increase in $CO_2$ between 88-138% (DfT-Low and Central/High respectively).

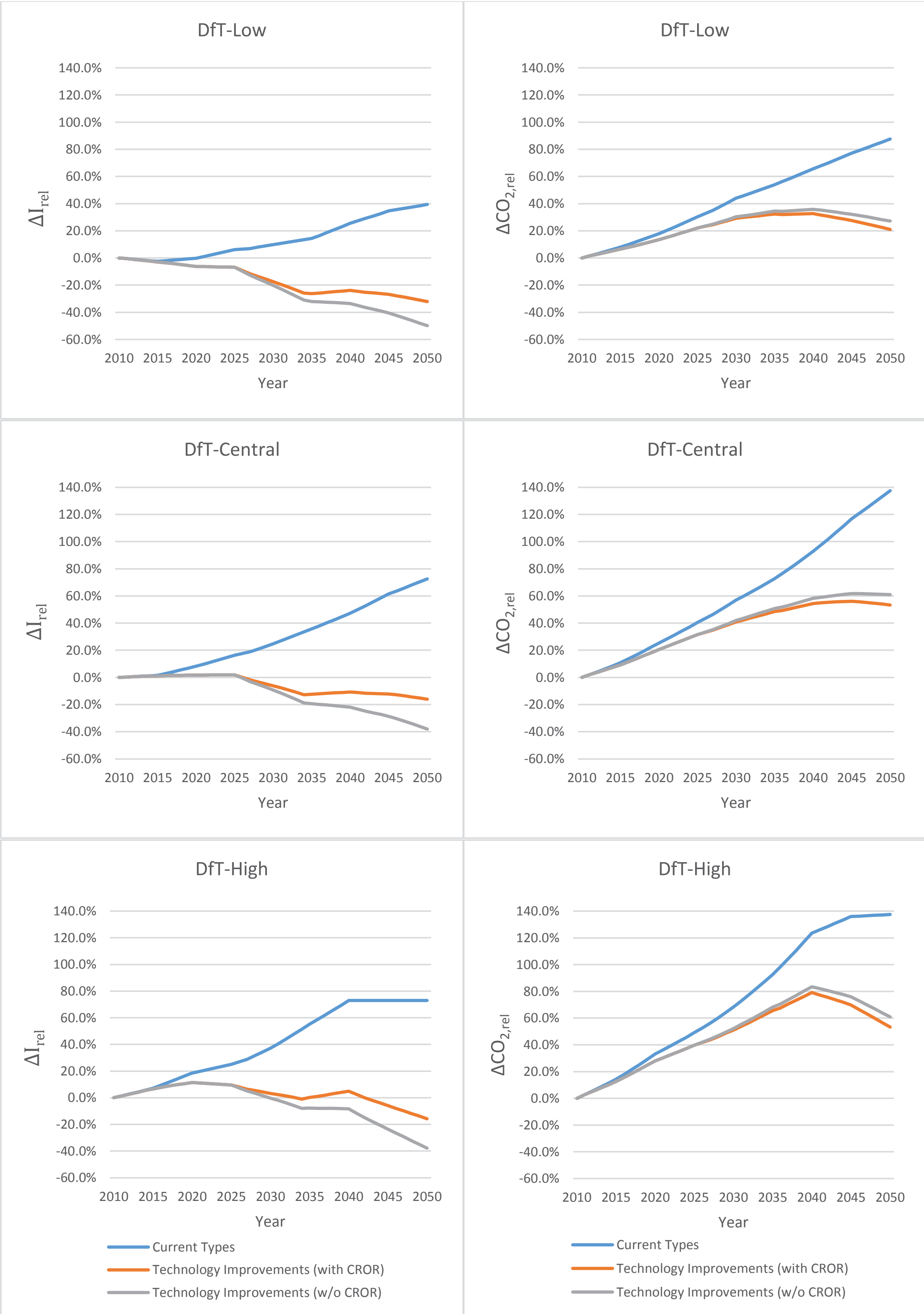


Figure 1 – Noise (left) and $CO_2$ (right) forecasts for the DfT air traffic projections Low (top), Central (middle) and High (bottom).

If it is assumed the penetration of aircraft of generations G1 and G2 in the fleet, with and without the replacement of SMRT aircraft with CROR (orange and grey lines respectively), by 2050 the sound intensity is estimated to be reduced in a value between -16% (DfT-Central/High with CROR) and -50% (DfT-Low without CROR), and the $CO_2$ is estimated to be increased in a value between 21% (DfT-Low with CROR) and 61% (DfT-Central/High without CROR). Therefore, regardless the air traffic projection and technology scenario considered, an incremental trend is observed for aviation CO2 and a decremental trend is observed for sound intensity emitted by the aircraft fleet in service. Moreover, the introduction of CROR is estimated to reduce the aviation $CO_2$ in 7% (by 2050), but at the expense of increasing the aircraft fleet sound intensity in 18% (by 2050).

### 4.2 Fuel-burn Efficiency vs. Aircraft Noise Efficiency

As shown in Table 6, although a significant increase in the fuel-burn and the sound intensity emitted is observed from the small to the very large aircraft, when the fuel-burn and the sound intensity is expressed as units per passengers carried and kilometers travelled, wide-body aircraft (LRT and LRQ) are found as more efficient than narrow-body aircraft (RJ and SMRT). Note that the total sound intensity emitted and the aircraft noise efficiency (ANE) was calculated as indicated in Sections 2.3 and 2.4, and fuel-burn data was obtained from the ICAO Aircraft Engine Emissions Databank (https://www.easa.europa.eu/document-library/icao-aircraft-engine-emissions-databank).

Table 6 – LTO total fuel-burn and sound intensity for each aircraft category of the current generation (G0).

| Aircraft category | LTO Total Fuel-burn | | LTO Total Sound Intensity | |
|---|---|---|---|---|
| | kg | $10^{-4}$ Kg/pax-km | $10^{-4}$ Watts/m$^2$ | $10^{-10}$ Watts/m$^2$pax-km (ANE) |
| RJ | 526.01 | 27.45 | 3.48 | 16.62 |
| SMRT | 848.41 | 16.07 | 5.89 | 10.93 |
| LRT | 2019.82 | 9.88 | 12.71 | 5.95 |
| LRQ | 3316.30 | 5.67 | 43.67 | 7.64 |

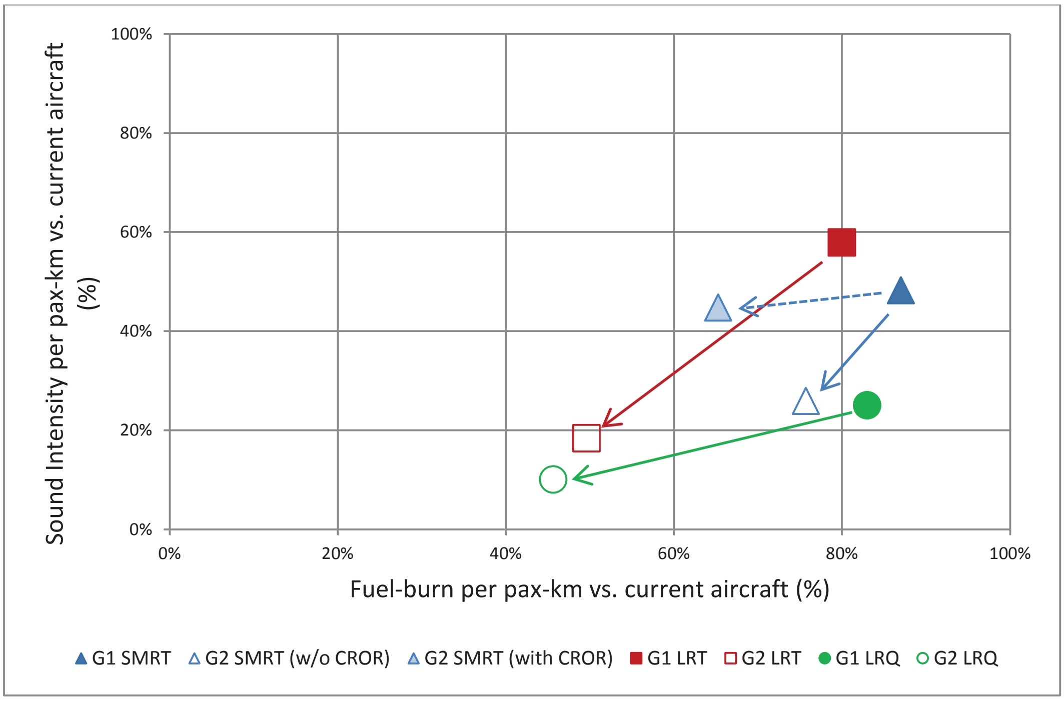


Figure 2 – Fuel-burn per pax-km vs. sound intensity per pax-km for imminent (G1) and future (G2) generations (relative to the current types), for each aircraft category.

Figure 2 shows the improvements in fuel-burn per pax-km and ANE, compared to current generation G0, for each aircraft category (SMRT – triangles, LRT – squares and LRQ – circles) of generations G1 (filled symbols) and G2 (unfilled symbols). From the data plotted in Figure 2, which are based on the technology projections suggested by ICAO CAEP and SA experts (8, 9), it is reasonable to assume that the development of novel aircraft technologies is primarily driven by the reduction of aircraft noise. Regarding aircraft generation G2, the fuel-burn per pax-km of the categories considered ranges between the 46-76% of current types, while the ANE ranges between 10-45% of current types. A special case is the SMRT category of generation G2, when the fuel-burn per pax-km and the ANE varies between 65-76% and 45-26% of current types, with and without the introduction of CROR.

### 4.3 Contribution of each Aircraft Category to Sound Intensity and $CO_2$ Emission

Figure 3 shows the contribution (i.e. (categoty/whole fleet) · 100) of each aircraft category to the total sound intensity (top) and $CO_2$ (bottom) emitted by the whole aircraft fleet in the UK, with (left) and without (right) the introduction of CROR.

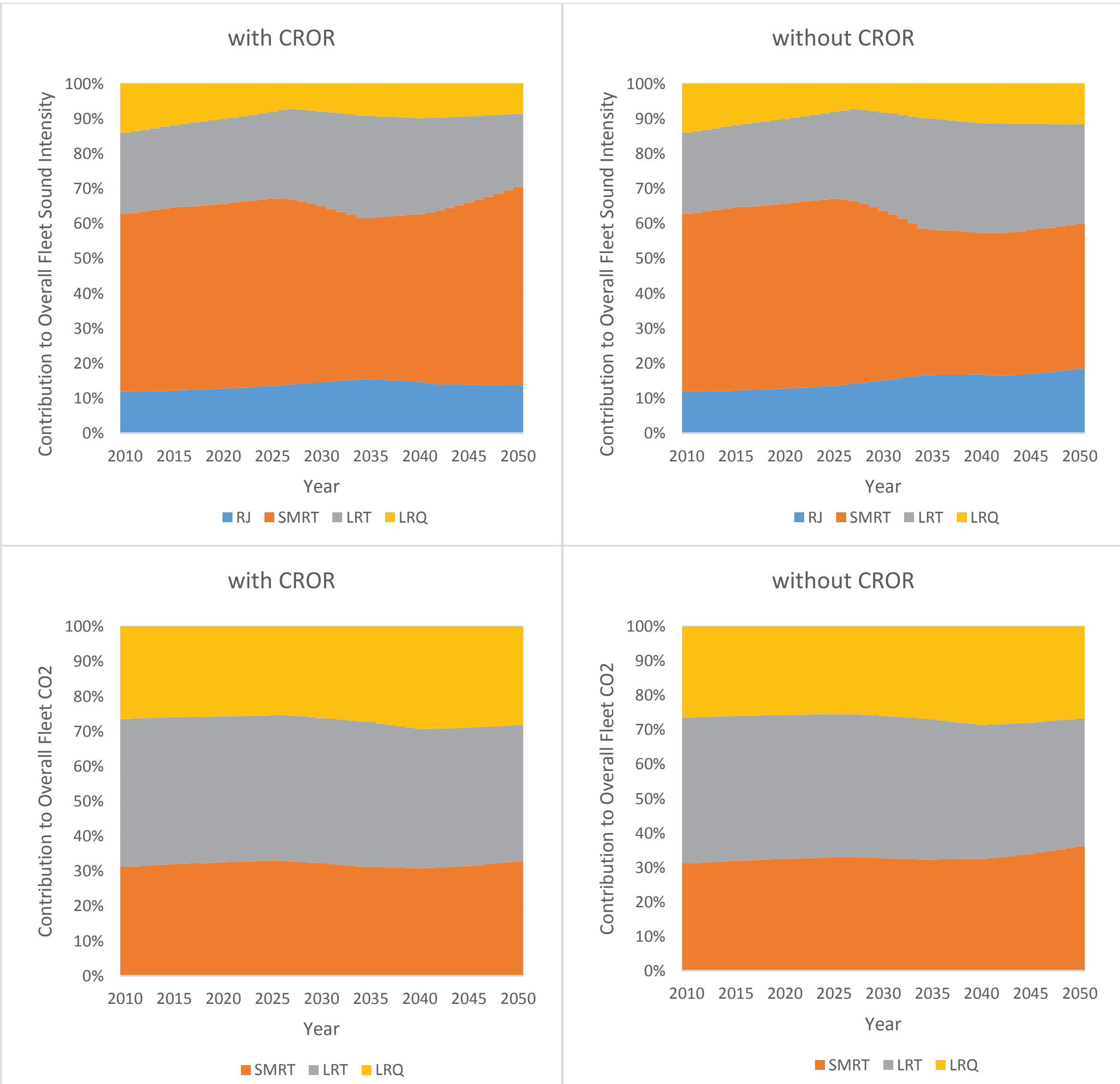


Figure 3 – Contribution of each aircraft category to the total sound intensity (top) and $CO_2$ (bottom) emitted by the whole aircraft fleet in the UK, with (left) and without (right) the introduction of CROR.

As observed in Figure 3, although the main contributor to the CO2 emitted is the LRT category, there are not significant differences between categories. Regarding the sound intensity emitted, the main contributor by far is the SMRT category. On average, about half of the sound intensity is contributed by the SMRT category, and only between 35-38 % (depending on the noise technology scenario) is contributed by LRT and LRQ categories.

On the other hand, while the introduction of CROR will have a negligible influence on the contribution of SMRT to the whole aircraft fleet $CO_2$, it will make even more significant the dominance of SMRT category as the main contributor to the sound intensity emitted by the whole aircraft fleet in the long-term.

## 5. CONCLUSIONS

In this paper only technology improvements for fuel-burn and noise reduction are considered. Assuming the noise reduction rates suggested by the ICAO CAEP experts, and for all the air traffic projections evaluated, significant reductions in sound intensity emitted by the aircraft fleet in the UK are estimated as compared to current levels. However, in terms of the aviation $CO_2$ in the UK, important increases are estimated, as compared to current levels, for each air traffic projection and technology scenario (as suggested by the SA experts) evaluated. In order to significantly reduce the aviation $CO_2$ values, as compared to current levels, the use of sustainable fuels and a carbon trading scheme will be required.

The assumptions of ICAO CAEP and SA experts in terms of $CO_2$ and noise reduction point out the noise factor as the main driver for the development of technology improvements to be incorporated in novel aircraft designs. Based on the projections considered in this work, for each improvement of 1% in reducing fuel-burn, a 2.3% noise reduction was found.

With the technology and air traffic scenarios assumed in this work, it is estimated that the introduction of CROR will cause in the long-term a relatively small reduction in aviation $CO_2$, but at the expense of significantly increasing the sound intensity emitted by the aircraft fleet in the UK. Moreover, if CROR are introduced, the dominance of SMRT category as the main contributor to the sound intensity emitted by the whole aircraft fleet is expected to notably increase in the long-term.

## ACKNOWLEDGEMENTS

This work was partly supported by the Engineering and Physical Science Research Council (grant number EP/M026868/1).

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