

# ENVIRONMENTAL TRENDS IN AVIATION TO 2050

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Each three-year work cycle, the International Civil Aviation Organization (ICAO) Committee on Aviation Environmental Protection (CAEP) develops an analysis of environmental trends in aviation to include:

- Aircraft Emissions that affect the Global Climate;
- Aircraft Noise; and
- Aircraft Emissions that affect Local Air Quality (LAQ).

CAEP aims to use the latest input data and related assumptions to assess the present and future impact and trends of aircraft noise and aircraft engine emissions.

## Trends in Aviation Emissions that affect the Global Climate

The assessment of GHG trends is based on the latest CAEP central demand forecast using a base year of 2010; the validity of which was assessed in the CAEP/10 (2016) cycle. Forecasted years included 2020 and 2030 with an extension to 2040 and results extrapolated to 2050. Data presented for 2005 and 2006 are reproduced from prior trends assessments.

Three models contributed results to the GHG trends assessment: US Federal Aviation Administration's (FAA) Aviation Environmental Design Tool (AEDT), EUROCONTROL's IMPACT, and Manchester Metropolitan University's Future Civil Aviation Scenario Software Tool (FAST). Key databases utilized in this assessment included the AEDT Airports Database, Campbell-Hill, the Growth and Replacement Fleet Database, and the Common Operations Database (COD), which are all proprietary databases, including Campbell-Hill which is owned and maintained by Airlines for America (A4A).

**Table 1** summarizes the nine full-flight fuel burn and CO<sub>2</sub> emissions scenarios developed for the assessment of trends for aircraft emissions that affect the global climate.

The trends presented were developed in the context of a longer-term view. Short term changes in global fuel efficiency can be affected substantially by a wide range of factors such as fluctuations in fuel prices, and global economic conditions. **Figure 1** provides results for global full-flight fuel burn for international aviation from 2005 to 2040, and then extrapolated to 2050. The fuel burn analysis considers the contribution of aircraft technology, improved air traffic management, and infrastructure use (i.e., operational improvements) to reduce fuel consumption. The figure also illustrates the fuel burn that would be expected if ICAO's 2 per cent annual fuel efficiency aspirational goal were achieved.

**Figure 2** puts these contributions in context with the uncertainty associated with the forecasted demand, which is notably larger than the range of potential contributions from technological and operational improvements. Despite this uncertainty, the baseline trends forecast is broadly consistent with other published

aviation forecasts. The trends forecast, which is for revenue tonne kilometres (RTK) and international aviation, shows a 20 year (2010-2030) compound average annual growth rate (CAGR) of 5.3 per cent. By way of comparison, using revenue passenger kilometres (RPK) for all traffic as the forecast measurement, Boeing's Airbus' and Embraer's most recent 2015 forecasts have 20 year (2014-2034) CAGRs of 4.9 per cent, 4.6 per cent and 4.9 per cent respectively<sup>1</sup>. The CAEP's RPK 20 year forecast (2010-2030) has a baseline forecast of 4.9 per cent, with a low outlook at 4.2 per cent and high at 5.7 per cent. While acknowledging the different forecast units and coverage, the trends baseline outlook shows reasonable alignment with the aviation industry and the most recent CAEP view of future aviation growth in the early 2010s.

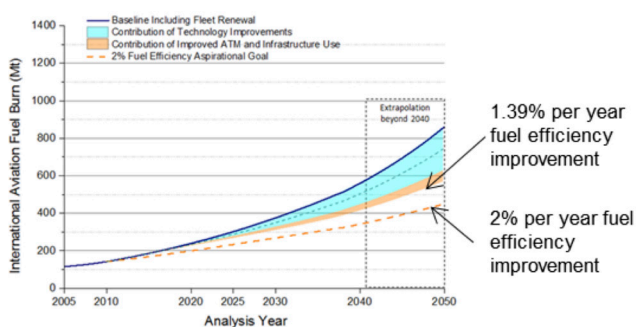
The results presented in Figures 1 and 2 are for international aviation only. In 2010, approximately 65 per cent of global aviation fuel consumption was from international aviation. Based on CAEP/MDG's analysis, this proportion is expected to grow to nearly 70 per cent by 2050.

**Figure 3** presents full-flight CO<sub>2</sub> emissions for international aviation from 2005 to 2040, and then extrapolated to 2050. This figure only considers the CO<sub>2</sub> emissions associated with the combustion of jet fuel, assuming that 1 kg of jet fuel burned generates 3.16 kg of CO<sub>2</sub>. As with the fuel burn analysis, this analysis considers the contribution of aircraft technology, improved air traffic management and infrastructure use (i.e., operational improvements). In addition, the range of possible CO<sub>2</sub> emissions in 2020 is displayed for reference to the global aspirational goal of keeping the net CO<sub>2</sub> emissions at this level. Although not displayed in a separate figure, the demand uncertainty effect on the fuel burn calculations shown in Figure 2 has an identical effect on the CO<sub>2</sub> results. Based on the maximum anticipated fuel consumption in 2020 (Scenario 1) and the anticipated Scenario 9 fuel consumption in 2040, a minimum CO<sub>2</sub> emission gap of 523 Mt is projected in 2040. Extrapolating Scenario 9 to 2050 results in a 1,039 Mt gap.

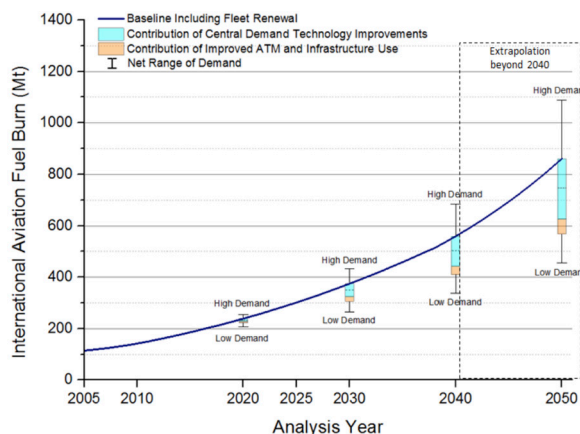
Scenario	Name	Technology Improvement	Operational Improvement
1	Baseline Including Fleet Renewal	None	None
2	Low Aircraft Technology and Moderate Operational Improvement	0.96%/annum, 2010-2015 0.57%/annum, 2015-2050	CAEP/8 IE Lower Bound
3	Moderate Aircraft Technology and Operational Improvement	0.96%/annum, 2010-2050	CAEP/8 IE Lower Bound
4	Advanced Aircraft Technology and Operational Improvement	1.16%/annum, 2010-2050	CAEP/8 IE Upper Bound
5	Optimistic Aircraft Technology and Advanced Operational Improvement	1.50%/annum, 2010-2050	CAEP/8 IE Upper Bound
6	Low Aircraft Technology and CAEP/9 Independent Expert (IE) Operational Improvement	0.96%/annum, 2010-2015 0.57%/annum, 2015-2050	CAEP/9 IE
7	Moderate Aircraft Technology and CAEP/9 IE Operational Improvement	0.96%/annum, 2010-2050	CAEP/9 IE
8	Advanced Aircraft Technology and CAEP/9 IE Operational Improvement	1.16%/annum, 2010-2050	CAEP/9 IE
9	Optimistic Aircraft Technology and CAEP/9 IE Operational Improvement	1.50%/annum, 2010-2050	CAEP/9 IE

**Table 1.** Full-Flight Fuel Burn and CO<sub>2</sub> Scenarios.

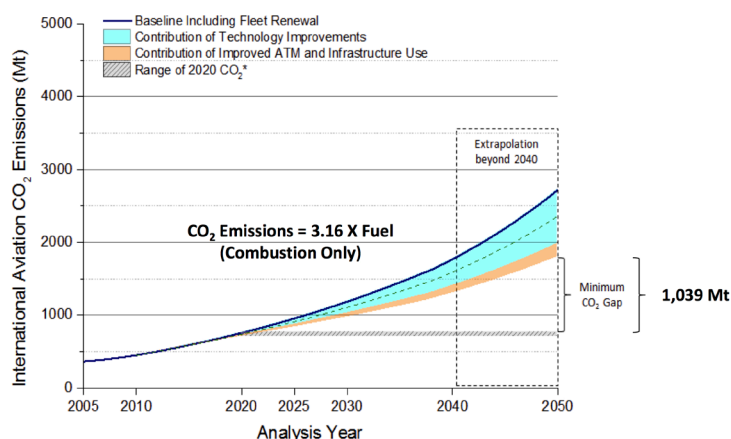
Note: Independent Expert is represented as IE. In CAEP/8 (2010), IEs provided a range of operational improvements in the form of a lower bound and upper bound.



Dashed line in technology contribution silver represents the "Low Aircraft Technology Scenario".  
Note: Results were modelled for 2005, 2006, 2010, 2020, 2025, 2030, and 2040 then extrapolated to 2050.



**Figure 2.** Range of Uncertainties Associated with Demand Forecast, 2005 to 2050



\*Actual carbon neutral line is within this range  
Dashed line in technology contribution silver represents the "Low Aircraft Technology Scenario".  
Note: Results were modelled for 2005, 2006, 2010, 2020, 2025, 2030, and 2040 then extrapolated to 2050.

**Figure 3.** CO<sub>2</sub> Emissions Trends from International Aviation, 2005 to 2050

### Contribution of Alternative Fuels to GHG Trends Assessment

CAEP was charged with calculating estimates of alternative jet fuel (AJF) contributions to fuel replacement and life cycle GHG emissions reductions in the Trends Assessment out to 2050. Analyses were performed for 2020 and 2050. The short-term scenarios for AJF availability were established from fuel producers’ announcements regarding their production plans from State-sponsored production plans, if associated with ICAO Member State target. For the long-term scenarios, CAEP assessed future jet fuel availability by first estimating the primary bioenergy potential constrained by selected environmental and socio-economic factors; by second estimating the proportion of bioenergy potential that could actually be achieved or produced; and finally by exploring the quantity of AJF that could be produced from the available bioenergy. AJF availability was calculated including 9 different groups of feasible feedstocks (starchy crops; sugary crops; lignocellulosic crops; oily crops; agricultural residues; forestry residues; waste fats, oils and greases; microalgae; municipal solid waste (MSW)). The final values provided by CAEP to MDG include potential total global production and an average Life Cycle Assessment (LCA) value based on the share of different fuel types that contribute to each scenario. The LCA values are not intended to be applied separately to regional forecasts.

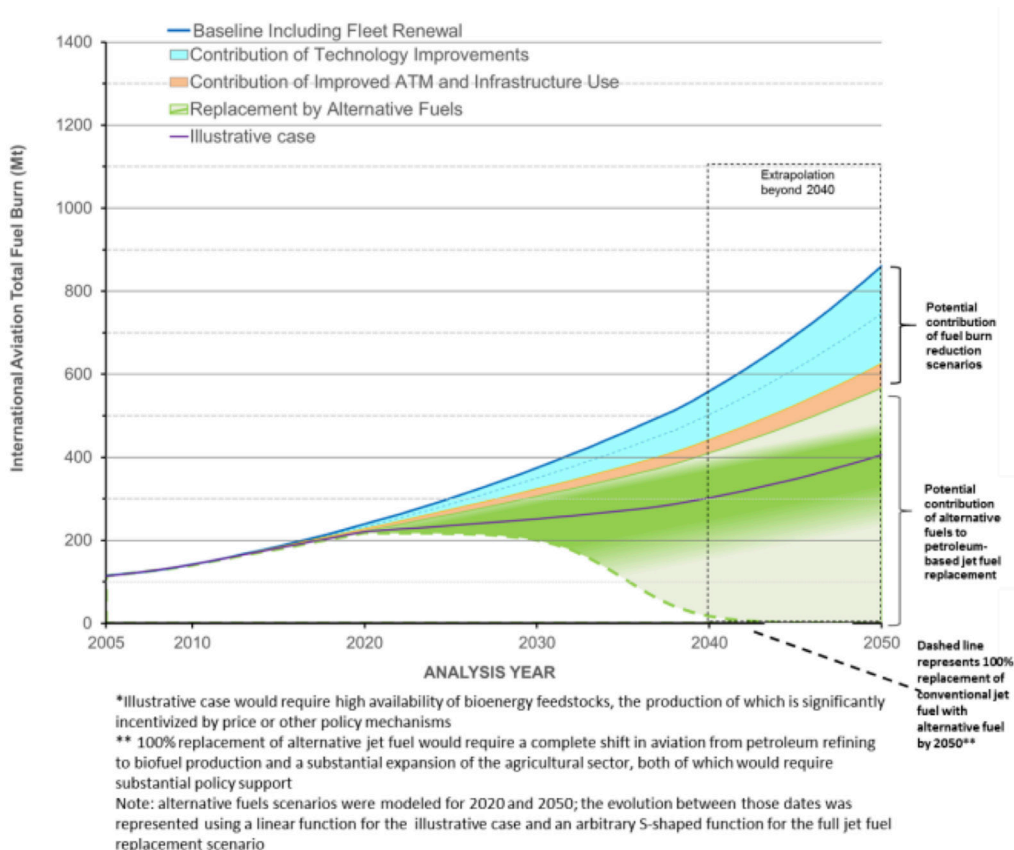
For 2020, there were six production estimates and two GHG LCA estimates (low and high), resulting in 12 possible GHG

emissions scenarios. The 2020 scenarios provide up to 2 per cent petroleum-based fuel replacement and up to 1.2 per cent GHG emissions reductions.

For 2050, CAEP calculated 60 production achievement scenarios and two GHG emissions scenarios resulting in 120 scenarios. Certain global conditions, economic investments, and policy decisions are assumed as part of each scenario definition and would be necessary to reach the associated outcome of alternative fuel production and GHG reductions.

The trends assessment figures for international aviation shown below include the range of CAEP results and an “illustrative” scenario that achieves 19 per cent net CO<sub>2</sub> emissions reduction assuming significant policy incentives and high biomass availability. Fuel replacement results for international aviation can be found in **Figure 4**. See **Figure 5** for net CO<sub>2</sub> emissions results. The amount of AJF and the associated CO<sub>2</sub> emissions reductions were allocated proportionally between international and domestic use based on projected fuel demand (65 per cent and 35 per cent in 2010, respectively).

For 2020 and 2050, total petroleum-based fuel amounts for the different fuel demand scenarios were multiplied by the specific CO<sub>2</sub> combustion emissions factor of 3.16 to get baseline GHG emissions shown in **Figure 5**. Calculations of GHG emissions reduction were performed according to the following formula provided by the CAEP Market Based Measure Task Group:



**Figure 4.** Aircraft Fuel Burn from International Aviation, 2005 to 2050 Updated to Include Potential Replacement of Jet Fuel with Alternative Fuels

**Total Emissions** =  $3.16 \times (\text{CJF} + \text{AJF} \times (\text{LCA\_AJF} / \text{LCA\_CJF}))$   
**Where** CJF = conventional jet fuel, AJF = alternative jet fuel, and  
**LCA\_X** = life cycle CO<sub>2</sub> equivalent emissions of fuel X.<sup>2</sup>

The GHG reduction “wedge” was created by connecting the least contribution scenario values to each other and the greatest contribution values to each other. The 2020 “medium scenario without green diesel” was connected to the 2050 value for the illustrative scenario. CAEP elected to show linear growth for intermediate and high GHG reduction scenarios<sup>3</sup>.

Several of the 2050 scenarios that CAEP evaluated resulted in zero alternative jet fuel production and therefore no contribution to GHG emissions reduction<sup>4</sup>.

The zero AJF results are equivalent to the line associated with Scenario 9 for technology and operational improvements as described above. The scenario with the greatest contribution to GHG emissions reduction could supply more alternative jet fuel than is anticipated to be used in 2050. For the purposes of this analysis, production for the highest contribution scenario is ramped up to full replacement in 2050 based on Scenario 9.

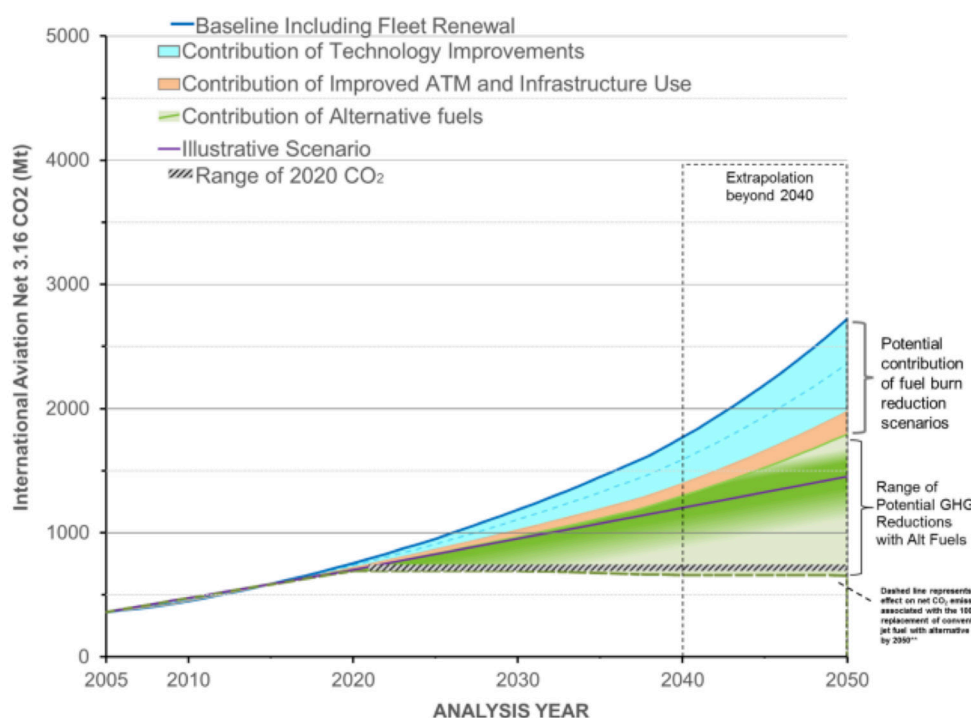
If industry growth were to follow an s-shaped curve, the highest growth rates would occur around 2035, in which 328 new large biorefineries would need to be built each year at an approximate capital cost of US\$ 29 Billion to US\$ 115 Billion per year. Lower growth rates would be required in years closer

to 2020 and 2050. Achieving this level of emissions reduction would also require the realization of the highest assumed increases in agricultural productivity, highest availability of land for feedstock cultivation, highest residue removal rates, highest conversion efficiency improvements, largest reductions in the GHG emissions of utilities, as well as a strong market or policy emphasis on bioenergy in general, and alternative aviation fuel in particular. This implies that a large share of the globally available bioenergy resource would be devoted to producing aviation fuel, as opposed to other uses.

Achievement of carbon neutral growth at 2020 emissions levels out to 2050 would require nearly complete replacement of petroleum-based jet fuel with sustainable alternative jet fuel besides the implementation of aggressive technological and operational scenarios. The future development and use of alternative fuels will highly depend on the policies and incentives in place for such fuels. Based on the analysis assumptions, if enough alternative jet fuel were produced in 2050 to completely replace petroleum-derived jet fuel, it would reduce net CO<sub>2</sub> emissions by 63 per cent.

### Trends in Aircraft Full Flight NO<sub>x</sub> Emissions

The following scenarios were assessed for Full Flight NO<sub>x</sub>: Scenario 2 is the moderate aircraft technology and CAEP/9 (2013) Independent Expert (IE) Operational Improvement case that assumes aircraft NO<sub>x</sub> improvement based upon achieving 50 per cent of the reduction from current NO<sub>x</sub> emission levels



\*Illustrative case would require high availability of bioenergy feedstocks, the production of which is significantly incentivized by price or other policy mechanisms  
 \*\* 100% replacement of alternative jet fuel would require a complete shift in aviation from petroleum refining to biofuel production and a substantial expansion of the agricultural sector, both of which would require substantial policy support

**Figure 5.** Aircraft CO<sub>2</sub> Emissions from International Aviation, 2005 to 2050, Updated to Include Alternative Fuels Life Cycle Emissions Reductions

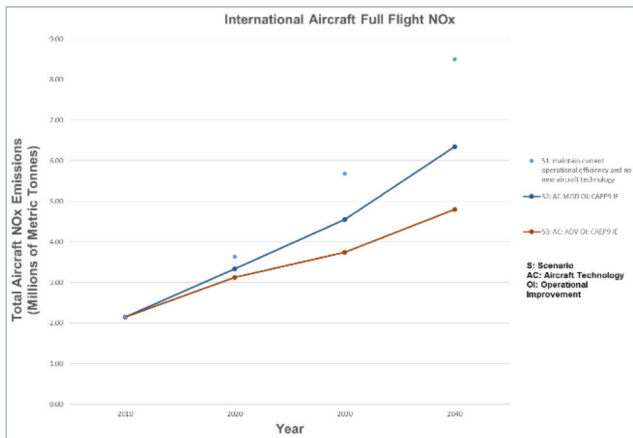
to the NOx emissions levels by CAEP/7 (2007) NOx IE goals review (-60 per cent +/- 5 per cent of current CAEP/6 (2004) NOx Standard) for 2030, with no further improvement thereafter.

Scenario 3 is the advanced aircraft technology and CAEP/9 (2013) IE Operational Improvement case that assumes aircraft NOx improvement based upon achieving 100 per cent of the reduction from current NOx emission levels to the NOx emissions levels by CAEP/7 (2007) NOx IE goals review (-60 per cent +/- 5 per cent of current CAEP/6 (2004) NOx Standard) for 2030, with no further improvement thereafter.

Two models contributed results to the full flight NOx trends assessment: (1) FAA's AEDT; and (2) EUROCONTROL's IMPACT. MDG results for international operations are shown in **Figure 6**. The 2010 baseline NOx value is 2.15 MT. In 2040, the NOx value ranges from about 4.81 MT with Scenario 3 to 6.35 MT with Scenario 2.

**Interpretation**

In 2010, international aviation consumed approximately 142 million metric tonnes of fuel, resulting in 448 million metric tonnes (Mt, 1kg x 10<sup>9</sup>) of CO<sub>2</sub> emissions. By 2040, fuel consumption is projected to have increased 2.8 to 3.9 times the 2010 value,



**Figure 6.** International Aircraft Full Flight NOx

while revenue tonne kilometres are expected to increase 4.2 times under the central demand forecast. By extrapolating to 2050, fuel consumption is projected to have increased 4 to 6 times the 2010 value, while revenue tonne kilometres are expected to increase 7 times under the central demand forecast.

Under Scenario 9 as defined in Table 1, aviation fuel efficiency, expressed in terms of volume of fuel per RTK, is expected to improve at an average rate of 1.4 per cent per annum to 2040, and at 1.39 per cent per annum, if extrapolated to 2050. While in the near term (2010 to 2020), efficiency improvements from technology and improved ATM and infrastructure use are expected to be moderate, they are projected to accelerate in the mid-term (2020 to 2030). During the 2020 to 2030 period, fuel efficiency is expected to improve at an average rate of 1.76 per cent per

annum under Scenario 9. The magnitude of the modelled fuel efficiency improvements is as expected given the 1.5 per cent per annum technology improvement associated with Scenario 9, and the variability of the forecasted RTK. This analysis shows that additional technological and operational improvements beyond even those described in Scenario 9 will be required to achieve the global aspirational goal of 2 per cent per annum fuel efficiency. In 2020, it is expected that international aviation will consume between 216 and 239 Mt of fuel, resulting in 682 to 755 Mt of CO<sub>2</sub> emissions. Under the range of 2020 scenarios, it is estimated that up to 2 per cent of this fuel consumption could consist of sustainable alternative fuels in 2020. Significant uncertainties exist in predicting the contribution of sustainable alternative fuels in 2050. Based on scenarios considered by CAEP, it is possible that up to 100 per cent of the CO<sub>2</sub> emissions gap could be closed with sustainable alternative fuels in 2050, but this would require nearly complete replacement of petroleum-based fuels with sustainable alternative jet fuel. Complete replacement would require approximately 170 new large biorefineries to be built every year from 2020 to 2050, at an approximate capital cost of US\$15 Billion to US\$60 Billion per year if growth occurred linearly.

Achieving this level of emissions reduction would also require the realization of the highest assumed increases in agricultural productivity, highest availability of land for feedstock cultivation, highest residue removal rates, highest conversion efficiency improvements, largest reductions in the GHG emissions of utilities, as well as a strong market or policy emphasis on bioenergy in general, and alternative aviation fuel in particular. This implies that a large share of the globally available bioenergy resource would be devoted to producing aviation fuel, as opposed to other uses.

Even under this scenario, achieving carbon neutral growth exclusively from the use of sustainable alternative fuels is unlikely to happen in 2021 or shortly thereafter as for the production of alternative fuels an initial ramp-up phase is required before production can reach the levels mentioned above.

**Trends in Aircraft Noise**

A range of scenarios were developed for the assessment of aircraft noise trends, as shown in **Table 2**.

Scenario 1 is the sensitivity case that assumes the operational improvements necessary to maintain current operational efficiency, but does not include any aircraft technology improvements beyond those available in 2010 production aircraft. Since Scenario 1 is not considered a likely outcome by the CAEP, it is purposely depicted in all graphics with no line connecting the modelled results in 2010, 2020, 2030, and 2040. The other scenarios assume increased implementation of both operational and technological improvements. Scenarios 2, 3, and 4 are assumed to represent the range of most likely outcomes.

For airports outside the United States (US) and Europe two different population sources were used to count people inside

Scenario	Name	Technology Improvement	Operational Improvement
1	Sensitivity Case	None	None
2	Low Aircraft Technology and Moderate Operational Improvement	0.3 EPNdB/annum, 2011 -2013	2 per cent reduction in contour area shape applied to population exposed.
3	Moderate Aircraft Technology and Operational Improvement	0.3 EPNdB/annum, 2011 -2030 0.1 EPNdB/annum, 2031 -2040	2 per cent reduction in contour area shape applied to population exposed.
4	Advanced Aircraft Technology and Moderate Operational Improvement	0.3 EPNdB/annum, 2011 -2040	2 per cent reduction in contour area shape applied to population exposed.

**Table 2.** Scenarios Developed for the Assessment of Aircraft Noise Trends

Note: EPNdB means Effective Perceived Noise Level in Decibels.

Scenario	Name	Technology Improvement	Operational Improvement
1	Sensitivity Case	None	None
2	Moderate Aircraft Technology and Operational Improvement	50 % CAEP/7 NOx Independent Expert goals for 2030, nothing thereafter	CAEP/9 IE
3	Advanced Aircraft Technology and Operational Improvement	100 % CAEP/7 NOx Independent Expert goals for 2030, nothing thereafter	CAEP/9 IE

**Table 3.** Scenarios Developed for the Assessment of Aircraft LAQ Trends

of contours (legacy GRUMP and the newer LANDSCAN).<sup>5</sup> Comparisons between GRUMP/LANDSCAN and census sources from the US, United Kingdom, and Mainland Europe yielded mixed results, with some airports having higher and some lower population counts. Consequently, population results were presented as an uncertainty range, showing both low and high values.

**Figure 7** provides results for the total global population exposed to aircraft noise above 55 DNL for 2010, 2020, 2030, and 2040. The 2010 baseline value ranges from a low of 21.4 to a high of 34.9. The population results assume 2010 levels throughout the

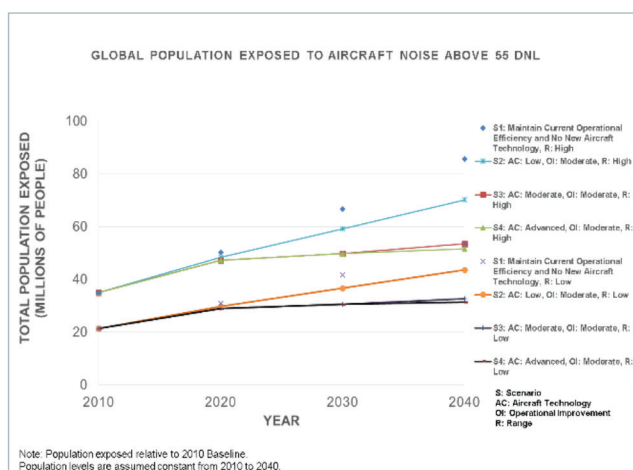
analysis period (2010 to 2040). Of note is that under an advanced aircraft technology and moderate operational improvement scenario, from 2030, aircraft noise exposure may no longer increase with an increase in traffic.

### Trends in Aircraft Emissions that affect Local Air Quality

A range of scenarios have also been developed for the assessment of aircraft emissions trends below 3,000 feet above ground level (AGL) that affect LAQ, particularly NOx, as shown in **Table 3**.

Again, Scenario 1 is the sensitivity case that assumes the operational improvements necessary to maintain current operational efficiency levels, but does not include any aircraft technology improvements beyond those available in 2010 production aircraft. Scenarios 2 and 3 assume aircraft NOx improvements based upon achieving some per cent (50 per cent and 100 per cent, respectively) of the reduction from the current NOx emission levels to the NOx emissions levels by CAEP/7 (2007) NOx Independent Expert goals review (about 60 per cent of the current CAEP/6 (2004) NOx Standard) for 2030, as well as fleet-wide operational improvements by region.

**Figure 8** provides results for NOx emissions below 3,000 feet AGL from international operations for 2010, 2020, 2030, and 2040. The 2010 baseline value is about 0.15 million metric tonnes (Mt, 1kg x 10<sup>9</sup>). In 2040, total NOx ranges from 0.32 Mt, with Scenario 3, to 0.42 Mt with Scenario 2.

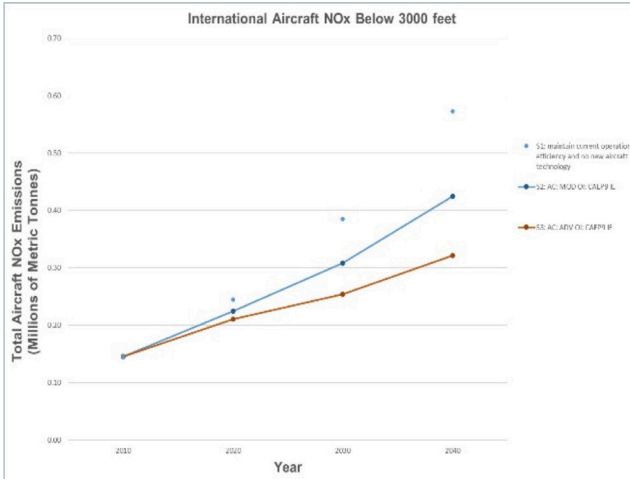


**Figure 7.** Total Global Population Exposed to Aircraft Noise Above 55 DNL

## CHAPTER 1

### AVIATION AND ENVIRONMENTAL - OUTLOOK

The results for PM emissions from international operations below 3,000 feet AGL follow the same trends as those for NO<sub>x</sub>. The 2010 baseline PM value is 914 metric tonnes. In 2040, total global PM is projected to be about 3,003 metric tonnes with Scenario 2.



**Figure 8.** Total International Aircraft NO<sub>x</sub> Below 3,000 Feet

## Conclusion

The CO<sub>2</sub> emissions that affect the global climate, and emissions that affect local air quality are expected to increase through 2050, but at a rate slower than aviation demand. Under an advanced aircraft technology and moderate operational improvement scenario, from 2030, aircraft noise exposure may no longer increase with an increase in traffic. However, it has to be kept in mind that the uncertainty associated with future aviation demand is notably larger than the range of contributions from technology and operational improvements.

International aviation fuel efficiency is expected to improve through 2050, but measures in addition to those considered in this analysis will be required to achieve ICAO's 2 per cent annual fuel efficiency aspirational goal. Sustainable alternative fuels have the potential to make a significant contribution, but sufficient data are not available to confidently predict their availability over the long term. Also, considering only aircraft technology and operational improvements, additional measures will be needed to achieve carbon neutral growth relative to 2020.

## References

1. [http://www.boeing.com/resources/boeingdotcom/commercial/about-our-market/assets/downloads/Boeing\\_Current\\_Market\\_Outlook\\_2015.pdf](http://www.boeing.com/resources/boeingdotcom/commercial/about-our-market/assets/downloads/Boeing_Current_Market_Outlook_2015.pdf);  
<http://www.airbus.com/company/market/forecast/>;  
<http://www.embraermarketoutlook.com/RPK-GPD.html>
2. This calculation provides an "in-flight" equivalent of CO<sub>2</sub> emissions reduction based on the life cycle values of the alternative fuels, which are used because reductions in atmospheric carbon from aviation biofuel use occur from feedstock production and fuel conversion and not from fuel combustion.
3. CAEP did not specify a function for connecting the 2020 results to the 2050 results in their outputs. However, CAEP did provide information on the range of options for connecting these results. CAEP anticipates that growth of a new industry such as that for AJF will follow an "S-shaped" trajectory, but it is not clear when investment, and therefore, growth of production capacity of the industry, will ramp up. Ramp up to alternative fuel production in 2050 is anticipated to be somewhere between linear and exponential growth (i.e., the lower end of the S-curve). Linear growth for intermediate and high net CO<sub>2</sub> emissions reduction scenarios is shown. No meaningful data exist in order to calibrate the curve. Therefore, values for intervening years between 2020 and 2050 for the AJF scenarios should be considered illustrative only.
4. These scenarios reflect a lack of bioenergy availability in general or a prioritization of other bioenergy usages over aviation.
5. <http://beta.sedac.ciesin.columbia.edu/data/set/grump-v1-population-count>  
<http://web.ornl.gov/sci/landscan/>