Environmental Trends in Aviation to 2070

By Gregg G. Fleming (USA DOT Volpe), Darren Rhodes (UK CAA), Roger Schaufele (USA FAA), Catherine Marthe (Switzerland FOCA), and David Pace (USA DOT Volpe)[1]

Background

At the end of each three-year work cycle, the International Civil Aviation Organization (ICAO) Committee on Aviation Environmental Protection (CAEP) assesses the future environmental trends in aviation that include:

- Full flight fuel burn and emissions.
- Aircraft noise.
- Aircraft engine emissions that affect Local Air Quality (LAQ).

The environmental trends discussed in this chapter are based on data from the latest CAEP/13 air travel mid demand forecast. The forecast utilized the base year of 2018 and forecast years of 2019, 2020, 2024, 2030, 2040, 2050, and 2070. The passenger and cargo forecasts were derived from ICAO's Long-Term Traffic Forecast (LTF), while the business jet forecast was developed from a new International Business Aviation Council (IBAC) aircraft delivery forecast. The traditional forecast development process was adjusted to account for the continued effect of COVID-19 on economic activity and traffic demand. Uncertainty around the effect of the pandemic on traffic demand is acknowledged through a series of forecast scenarios.

Data presented for years earlier than 2018 are reproduced from prior CAEP trends assessments. Trends results presented for fuel burn and emissions represent international aviation only, while noise results include both domestic and international operations. In 2018, approximately 65% of global aviation fuel consumption was from international aviation. According to the CAEP/13 traffic demand forecast, this proportion is expected to remain relatively stable out to 2070.

The trends presented here were developed in the context of a longer-term view, assuming no airport infrastructure or airspace operational constraints. However, these trends may be substantially impacted by a wide range of factors, including fluctuations in fuel prices, uptake of alternative jet fuels (AJF), and global economic conditions, including any residual effects of recovery from the COVID-19 pandemic.

Three environmental models contributed results to the full flight fuel burn and emissions trends assessment: FAA's Aviation Environmental Design Tool (AEDT); EUROCONTROL's Integrated Aircraft Noise and Fuel Burn & Emissions Modelling Platform (IMPACT); and Manchester Metropolitan University's Future Civil Aviation Scenario Software Tool (FAST). In addition, the US EPA's fuel burn and emissions tool, which is not a CAEP approved model, also provided limited results for comparisons.

Two distinct fleet evolution models were used: FAA's Fleet Builder (FB) and the EC/EASA/EUROCONTROL Aircraft Assignment Tool (AAT). The AEDT, FAST and US EPA results were based on the FB operations, while the IMPACT results were based on the AAT operations. Key databases utilized in this assessment include CAEP's Global Operations, Fleet, and Airports Databases.

During the CAEP/12 work cycle, a comprehensive introduction to the forecasting and environmental trends

1 Gregg G. Fleming and Darren Rhodes are co-Rapporteurs of the Modelling and Databases Group (MDG) of the ICAO Council's Committee on Aviation Environmental Protection (CAEP). Catherine Marthe and David Pace are co-Rapporteurs of the Forecasting and Economic Analysis Support Group (FESG).

assessment process was developed and is available for reference at ICAO's public website.

Traffic Demand Forecasts and COVID-19

The CAEP/13 environmental trends traffic demand forecast has a 2018 base year and 32-year forecast horizon through 2050 (with an additional forecast extension going out to 2070). It represents an update of the CAEP/12 forecast (which had the same 2018 base year), reflecting changes in global economic activity, including revised near-term traffic demand that was still being influenced by the recovery from the effects of the COVID-19 pandemic.

The traditional forecast development process was adjusted to account for the continued effect of COVID-19 on economic activity and traffic demand. Uncertainty around the effect of the pandemic on traffic demand is acknowledged through a series of forecast scenarios.

To account for the effect of COVID-19, a set of assumptions were developed and used to guide how the aviation industry was anticipated to continue to transition out of the pandemic driven downturn. These included expectations on the short-run path for when each market—passenger, cargo and business jet—would return to 2019 pre-COVID-19 levels under different scenarios (e.g., a delay in business travel recovery in the passenger market). Based on historical data it was determined that while the passenger market remained below 2019 levels, the cargo and business jet markets were largely back to pre-pandemic levels of activity at the time the CAEP/13 forecast was being developed.

The CAEP/13 forecast used updated macroeconomic forecast information incorporating the short- and long-run economic outlook as the world's economies moved out of the pandemic. Available historical data allowed for capturing the decline in demand beginning in 2020 and continuing through 2022. These data, and the guiding assumptions, allowed for identifying the point at which each market (i.e., passenger, cargo and business jet) is expected to return to their 2019 levels of activity, after which the long-term trends were used to guide the outlook.

Passenger market traffic demand shows a sharp decline in 2020 due to the pandemic (global revenue passenger kilometres (RPKs) declined by 67%) (Figure 1). The near-term recovery trajectories have global traffic demand returning to 2019 levels in 2024 for the high and mid scenarios, and 2025 for the low scenario. Over the 32-year forecast period, the CAEP/13 mid forecast has revenue passenger kilometres growing at an annual average rate of 3.4% for global and 3.5% for international demand (compared with 3.6% for global and international RPKs from the CAEP/12 COVID-19 LTF mid outlook).

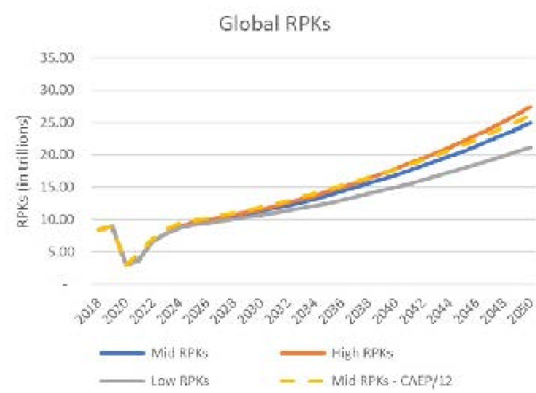

FIGURE 1: COVID-19 Global Passenger Forecast Scenarios.

The cargo market CAEP/13 forecast shows a decline in global demand of 15% in 2020 with a return to 2019 levels by 2021 for all scenarios (Figure 2). Over the course of the mid 32-year forecast, global freight tonne kilometres (FTKs) are expected to grow by 3.1% per annum (down from 3.5% in the CAEP/12 COVID-19 outlook), with international FTKs increasing by 3.0% per annum (compared with 3.4% in the CAEP/12 COVID-19 outlook).

Based on updated historical information, Business Jet operations saw a continued increase in operations during the height of the pandemic, counter to the CAEP/12 forecast that estimated a decline in operations (See Figure 3). For the CAEP/13 forecast, under the mid outlook operations are expected to increase on an average annual basis of 2.7% for the entire 32-year forecast period (unchanged from CAEP/12 outlook).

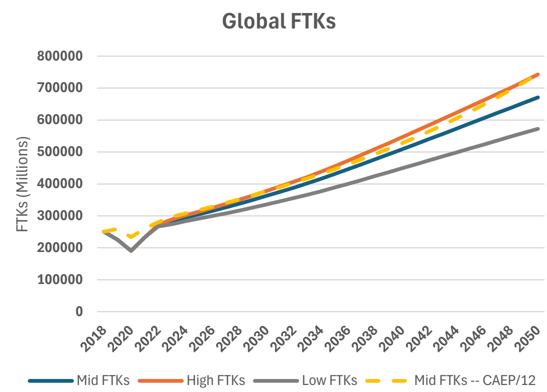

FIGURE 2: COVID-19 Global Cargo Forecast Scenarios.

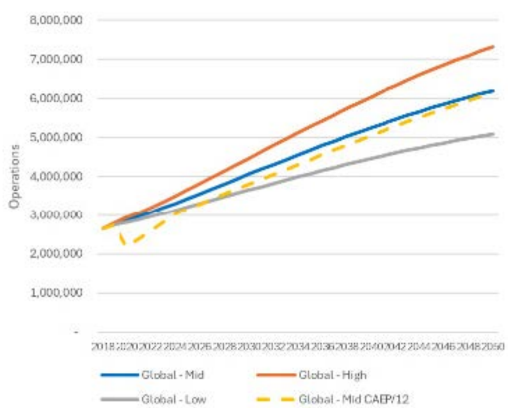

FIGURE 3: COVID-19 Global Business Jet Forecast Scenarios

A 20-year extension was added to the CAEP/13 traffic demand forecast, taking the forecast to 2070. The extension was developed using the methodology from CAEP/12, which leveraged information contained within the CAEP/13 forecast models.

Over the 52-year forecast period to 2070, passenger RPKs grow at an annual average rate of 3.3%, compared with 3.4% for the period from 2018 to 2050. International RPKs increase by an average of 3.3% per annum from 2018 to 2070, compared with 3.5% through 2050. Cargo FTKs are expected to increase at an average rate of 2.9% from 2018 through 2070, compared with 3.1% for the 32-years through 2050. International FTKs are expected to grow by an average of 2.8% per annum through 2070, compared with 3.0% growth through 2050. For the business jet market, operations are expected to grow at an average annual rate of 1.9% in the 52-year forecast period to 2070, compared with 2.7% growth between 2018 and 2050.

Full Flight Fuel Burn and Emissions Trends

Table 1 below summarizes the aircraft technology and operational scenarios developed for the assessment of trends for full flight fuel burn and aircraft emissions. The CAEP/13 trends assessment included full flight fuel burn, carbon dioxide (CO_2), nitrogen oxides (NO_X), and non-volatile particulate matter (nvPM).

Trends in Full-Flight Fuel Burn and Emissions

Figure 4 below shows the results for full flight (i.e., from departure gate to arrival gate) fuel burn for international aviation from 2005 to 2070. The analysis considered the impact of aircraft technology, improved air traffic management, and infrastructure use (i.e., operational improvements) on fuel consumption. The dashed line in the figure illustrates fuel burn that would be expected if ICAO's 2% annual fuel efficiency goal were to be achieved.

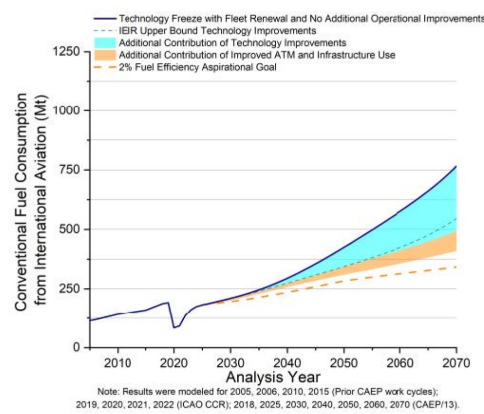

FIGURE 4: Fuel Burn from International Aviation, 2005 to 2070.

For 2070 Fuel Scenario 3 (IEIR[2] upper bound) aircraft technology accounts for a reduction of 220 Mt and operations accounts for an additional 85 Mt for a total reduction of 305 Mt as compared with Fuel Scenario 1. For Fuel Scenario 3 (IEIR lower bound) aircraft technology accounts for a reduction of 271 Mt and operations accounts for an additional 85 Mt for a total reduction of 356 Mt as compared with Fuel Scenario 1. Overall, Fuel Scenario 3 results in 27% and 46% reduction in fuel burn as compared with Fuel Scenario 1 in 2050 and 2070, respectively.

2 Independent Expert Integrated Review (IEIR)

Considering Fuel Scenario 3 (IEIR lower bound), an average fuel efficiency of 1.5% would be observed by 2050, increasing to about 1.6% by 2070. This would represent lower improvements compared to the ICAO 2% fuel efficiency aspirational goal for international aviation.

Figure 5 depicts the uncertainties associated with the forecasted demand, which is the largest contributor to uncertainty in fuel burn. The uncertainty in forecasted demand is roughly twice the size of the range in technology and operational improvements combined. Despite the range of uncertainties, the CAEP/13 forecast traffic trends are generally consistent with other published aviation forecasts. The CAEP/13 commercial market forecast for revenue passenger kilometres (RPK), shows a 20-year (2018 to 2038) compound average annual growth rate (CAGR) of 3.1%. By way of comparison, Boeing and Airbus RPK forecasts released in 2022 have CAGRs of 3.8%, and 3.6%, respectively for the period from 2019 to 2041.

Figure 6 presents full-flight CO_2 emissions for international aviation from 2005 to 2070; CO_2 emissions are based solely on the combustion of jet fuel, assuming that 1 kg of jet fuel burned generates 3.16 kg of CO_2. As with the previous fuel burn analysis, this CO_2 analysis considers the contribution of aircraft technology, improved air traffic management, and infrastructure use (operational improvements).

The delta between the CAEP/12 and CAEP/13 CO_2 trends baselines in 2040 is approximately 13%. Most of this variation can be attributed to differences between the central demand forecasts. Specifically, the CAEP/12 (2018) forecast was produced based on initial views of what the recovery from COVID-19 would look like. Those views were revised accordingly as part of preparing the CAEP/13 forecast, which was also based on a 2018 baseline.

Considering the range of fuel consumption scenarios (Table 1), the difference between the highest anticipated fuel consumption in 2019 (Fuel Scenario 1) and the lowest anticipated fuel consumption in 2050 (Fuel Scenario 4) results in a minimum CO_2 emission gap of 422 Mt in 2050 compared to 2019 emissions.

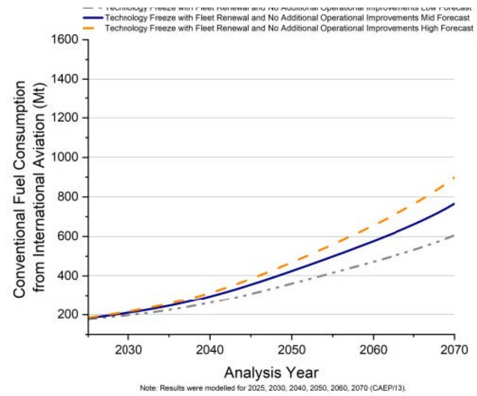

FIGURE 5: Range of Uncertainties Associated with Demand Forecast, 2024 to 2070.

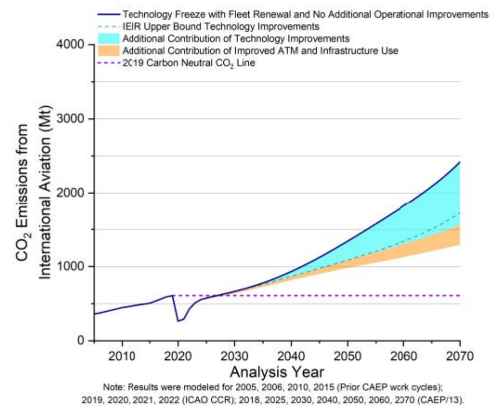

FIGURE 6: CO_2 Emissions from International Aviation, 2005 to 2070.

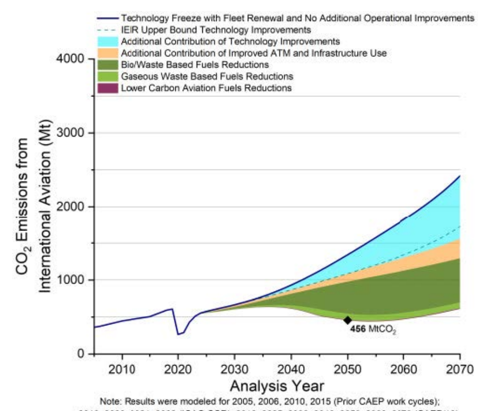

FIGURE 7: Combustion CO_2 Emissions from International Aviation, 2005 to 2070, Including Alternative Jet Fuels Life Cycle Emissions Reductions (Based on 3.16 kg of CO_2 per 1 kg of fuel burn).

Contribution of Alternative Fuels to Fuel Burn and CO_2 Trends

As shown in Figure 7 for international aviation, for the year 2050 and 2070, with alternative fuels replacement, there is a 53% reduction in residual CO_2 emissions in addition to the reduction from technology and operations improvements.

CAEP monitors long-term developments in CORSIA eligible fuels (CEFs) production and updates the fuels scenarios as needed for the ICAO Environmental Trends assessment. This includes projections for drop-in aviation fuels from renewable or waste resources, i.e., sustainable aviation fuels (SAF) and lower carbon aviation fuel (LCAF). Coordination of the various CEF activities within CAEP helps ensure consistency across analyses.

SAF production values were a blend of two distinct scenarios. To meet ICAO's 2030 goal, a blend of two scenarios were used for the years 2025 to 2030, and then the analysis switched back to the single scenario out to 2070. The SAF values beyond 2030 were based on assumptions about feedstock and technology success and could vary widely. The SAF scenario chosen is a gap analysis from previous work and is not supported by current production announcements.

Trends in Aircraft Full Flight NO_X and NVPM Emissions

Figure 8 shows the full flight NO_X emissions from international aviation. In 2018, NO_X emissions were calculated as 2.97 Mt. In 2070, NO_X emissions range from 10.46 Mt under Scenario 3 to 15.12 Mt under Scenario 1, representing up to a 4.66 Mt (7.18 Mt for global aviation) reduction with technology and operational improvements.

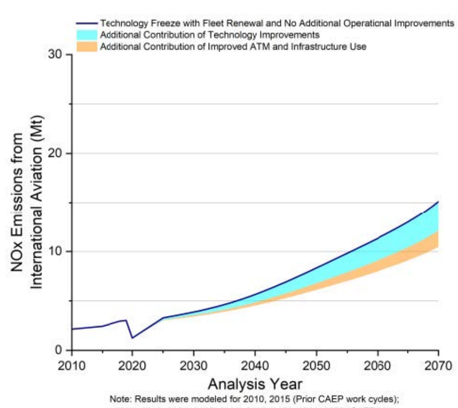

FIGURE 8: Full Flight NO_X Emissions from International Aviation, 2010 to 2070.

Figure 9 shows the full flight nvPM emissions trend from international aviation. In 2018, nvPM emissions were calculated as 6.99 kt. In 2070, nvPM emissions range from 12.92 kt under Scenario 3 to 24.75 kt under Scenario 1, representing up to a 11.83 kt (15.28 kt for global aviation) reduction with technology and operational improvements.

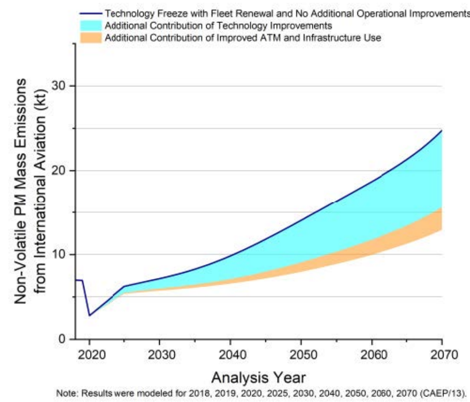

FIGURE 9: Full Flight nvPM Emissions from International Aviation, 2018 to 2070.

Trends in Aircraft Noise

Four scenarios were developed for the noise trends assessment, resulting in the total contour area and population inside the yearly average day-night level (DNL) contours of 55, 60, and 65 dB for 320 global airports, representing approximately 80% of global population exposure to aircraft noise. Population counts for airports in the US, Europe and Brazil used the latest available local census data. For all other airports, the NASA Gridded Population of the World version 4 was used.

Scenario 1 (CAEP/13 Baseline) assumes no further aircraft technology or operational improvements after 2018. Scenario 2 includes noise technology improvements of 0.1 EPNdB per annum for all aircraft entering the fleet from 2019 to 2070. Scenario 3 was meant to capture the COVID-19 delay with no noise technology improvement from aircraft entering the fleet from 2019 to 2023, and technology improvement of 0.2 EPNdB per annum for all aircraft entering the fleet from 2024 to 2070. Scenario 4 includes noise technology improvement of 0.2 EPNdB per annum for all aircraft entering the fleet from 2019 to 2070. For Scenarios 2, 3 and 4, an additional moderate operational improvement of 2% is applied for population

Scenario	Aircraft Technology: Per annum fuel burn improvement for fleet entering after 2018	Aircraft Technology: Emissions improvements against CAEP/7 IE NO_x Goal	Operational Improvements
Fuel 1 - Tech Freeze with No Operational Improvements	NA: use only base year (2018) in-production aircraft	NA	NA: maintain current operational efficiency levels
Fuel 2 - Moderate Aircraft Technology and Low Operational Improvements	0.96 percent 2018 to 2050; for 2051 to 2070, no additional improvements (Case 1) and continued 0.96 percent to 2070 (Case 2)	NA	Fleet wide CAEP/12 LTAG low operational improvement by route group
Fuel 3 – Independent Expert Integrated Review (IEIR) Technology and Medium Operational Improvements	IEIR by aircraft type improvement 2018 to 2050; for 2051 to 2070, no additional improvements (Case 1) and continued IEIR by aircraft type improvement (Case 2)	NA	Fleet wide CAEP/12 LTAG medium operational improvement by route group
Fuel 4 – LTAG, Advanced Tube and Wing (ATW) Medium Technology and Medium Operational Improvements	LTAG ATW medium technology improvement by aircraft type 2018 to 2050; for 2051 to 2070, no additional improvements (Case 1) and continued LTAG ATW medium technology improvement by aircraft type (Case 2)	NA	Fleet wide CAEP/12 LTAG medium operational improvement by route group
NO_x 1 - Technology Freeze with No Operational Improvements	NA: use only base year (2018) in-production aircraft	NA	NA: maintain current operational efficiency levels
NO_x 2 - CAEP/12 LTAG Low Operational, and 50% CAEP/7 IE Emissions Improvements	NA	50 percent of CAEP/7 IE NO_x Goal met by 2036 with no further improvement thereafter	Fleet-wide CAEP/12 LTAG low operational improvements by route group
NO_x 3 – CAEP/12 LTAG High Operational, and 100% CAEP/7 IE Emissions Improvements	NA	100 percent of CAEP/7 IE NO_x Goal met by 2036 with no further improvement thereafter	Fleet-wide CAEP/12 WG2 high operational improvements by route group
nvPM 1 - Technology Freeze with No Operational Improvements	NA: use only base year (2018) in-production aircraft	NA	NA: maintain current operational efficiency levels
nvPM 2 – CAEP/12 LTAG Low Operational, and CAEP/13 Moderate Technology Improvement	**CAEP/13 Moderate Technology Improvement**	NA	Fleet-wide CAEP/12 LTAG Low Operational Improvements by route group

TABLE 1: Fuel Burn and Emissions – Technology and Operational Improvement Scenarios

inside the 55, 60 and 65 dB contours.[3] Four modelling scenarios were included, and modelled for each of the future years, as follows: 2019, 2020, 2025 (scenario 1 only); and 2030, 2040, 2050, 2060, and 2070 (all 4 scenarios).

Figure 10 provides results for the total global 55 DNL[4] contour area (i.e., for 320 airports) for 2018 (base year), 2019, 2020, 2025 (scenario 1 only) and 2030, 2040, 2050, 2060 and 2070 for the four scenarios. Historical data modelled in the CAEP/11 work cycle is also shown for 2015. The 2018 contour area is 16,657 square km. This value decreases to 10,306 square km in 2020 due to COVID-19 pandemic and increases to 14,164 square km by 2025. In 2070 the technology freeze (Scenario 1) total

3 In order to show the COVID-19 pandemic related downturn and the recovery, 2019, 2020 and 2025 years were modelled for Scenario 1 (Technology Freeze with no Operational Improvement).

4 DNL 55 covers all the noise above 55 dB including 60 dB and 65 dB and DNL 60 covers all the noise above 60 dB including 65 dB.

global contour area is 32,887 square km and decreases to 22,240 square km with low technology improvements (scenario 2), to 15,723 square km with moderate technology improvements (scenario 3), and to 11,363 square km with the advanced technology improvements (scenario 4). The total population inside the 55 DNL contours was estimated to be 36 million in 2018 and could range from 78 million under Scenario 1 to 27 million under Scenario 4 in 2070; this is under the assumption that population density around airports does not vary in time.

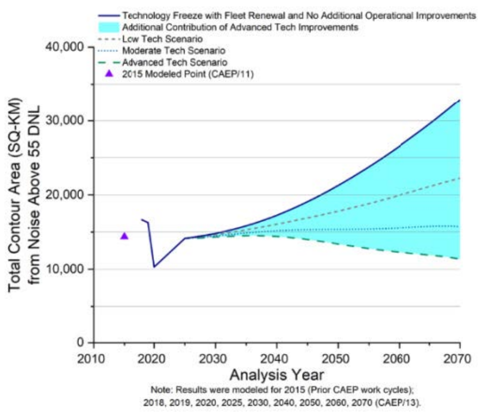

FIGURE 10: Total Global Aircraft Contour Area Above 55 dB DNL, for 320 Airports (km^2), 2015-2070.

Trends in Landing and Takeoff (LTO) Emissions

A range of scenarios was also developed for evaluation of aircraft emissions that occur below 3,000 feet above ground level; namely NO_X and total (volatile and non-volatile) particulate matter (PM). The NO_X and PM scenarios for LTO are equivalent to the those used in the full-flight trends assessment (Table 1).

NO_X emissions below 3000 feet from international aviation are shown in Figure 11. In 2050, technology and operational improvements could provide reductions of up to 0.14 Mt (36%) and 0.30 (36%) Mt in NO_X emissions for international and global aviation, respectively. By 2070, technology and operational improvements could provide reductions of up to 0.30 Mt (45%) and 0.66 Mt (45%) in NO_X emissions for international and global aviation, respectively.

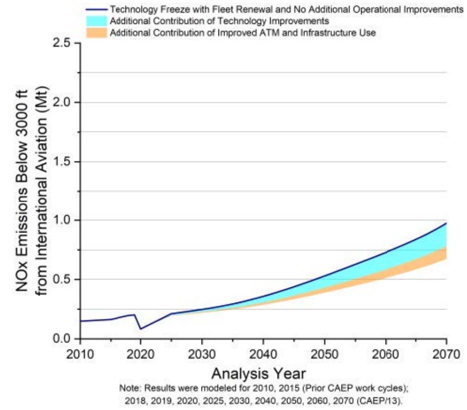

FIGURE 11: NO_X Emissions below 3000 ft from International Aviation, 2010 to 2070.

Non-volatile PM (nvPM) emissions below 3000 feet from international aviation are shown in Figure 12. In 2050, technology and operational improvements could provide reductions of up to 0.26 Kt (42%) and 0.54 (42%) Kt in nvPM emissions for international and global aviation, respectively. By 2070, technology and operational improvements could provide reductions of up to 0.50 Kt (48%) and 1.05 Kt (48%) in nvPM emissions for international and global aviation, respectively.

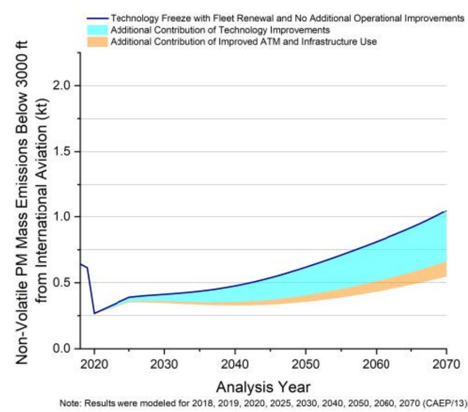

FIGURE 12: nvPM Emissions below 3000 ft from International Aviation, 2018 to 2070.

Conclusions

Full-flight and LTO emissions from international aviation are expected to increase through 2070 by 2 to 5 times 2018 levels, depending on the pollutant (CO_2, NO_x, nvPM, or PM) and the analysis scenario. Specifically for the full flight technology freeze scenario (Fuel Scenario 1), CO_2, NO_x, and nvPM are expected to increase by a factor of 4, 5 and 3.6, respectively. For LTO emissions (Fuel Scenario 1), NO_x and nvPM are expected to increase by a factor of 4.9 and 1.6, respectively. These factors are generally consistent for both international and global aviation. The total DNL 55 dB noise contour area at the 320 airports in the analysis could stabilize after 2025 under an advanced technology improvements scenario.

In 2018[5], international aviation consumed approximately 188 Mt of fuel, resulting in 593 Mt of CO_2 emissions. By 2070, fuel consumption is projected to increase 3 to 4.1 times the 2018 value, while revenue tonne kilometres (RTK) are expected to increase 5 times under the most recent forecasts (the 52-year [2018 to 2070] compound annual growth rate for RTKs is 3.2%). Assuming the most optimistic fuel technology improvements (Fuel Scenario 4), international fuel efficiency (volume of fuel per RTK) is expected to improve at an average rate of 1.5% per annum (2015 to 2050), increasing slightly to 1.6% by 2070. This indicates that ICAO's aspirational goal of 2% per annum fuel efficiency improvement is unlikely to be met by 2050. Aircraft technology, ATM and AJF combined have the potential to curb the growth in net CO_2 emissions from aviation in the longer-term (beginning in 2035), but this will likely necessitate significant investments. Furthermore, uncertainties associated with future aviation demand remain high.

References

1. ICAO. 2022 Environmental Report. https://www.icao.int/environmental-protection/pages/envrep2019.aspx.
2. Environmental Trends in Aviation to 2050. pp 24-31.
3. ICAO Environmental Trends: https://www.icao.int/environmental-protection/Pages/Environmental-Trends.aspx .

5 The CAEP/14 Environmental Trends is expected to have a 2024 base year.