Environmental Trends in Aviation to 2050

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Background

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

- Aircraft engine Greenhouse Gas (GHG) emissions that affect the global climate.
- 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/12 air travel mid demand forecast. The forecast utilized a base year of 2018 and future years of 2019, 2020, 2024, 2030, 2040, and 2050. 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. COVID-19 forecast scenarios were developed to capture the possible trajectories of the aviation industry as it moves out of the pandemic-driven downturn.

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/12 traffic demand forecast, this proportion is expected to remain relatively stable out to 2050.

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 the COVID-19 recovery.

Three environmental models contributed results to the fuel burn and emissions 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). In addition, the US Environmental Protection Agency's (EPA) fuel burn and emissions model provided results as a cross-check with the three CAEP-approved models.

Three models contributed results to the noise trends assessment: US FAA's AEDT, EC/EASA/EUROCONTROL's SysTem for AirPort noise Exposure Studies (STAPES), and UK Civil Aviation Authority's (CAA) Aircraft Noise Contour Model (ANCON).

Two distinct fleet evolution models were used: FAA's FleetBuilder (FB) and the EC/EASA/EUROCONTROL's Aircraft Assignment Tool (AAT). The AEDT, FAST and EPA results were based on FB operations, while the IMPACT estimates were based on AAT operations. Key databases

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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 assessment process was developed and is available for reference at ICAO public website[2].

Traffic Demand Forecasts and COVID-19

The CAEP/12 environmental trends traffic demand forecast has a 2018 base year and 32-year forecast horizon through 2050. The outbreak of COVID-19 in early 2020 meant that the normal forecast development process had to be altered to account for the near- and long-term effects of the pandemic on the global economy and commercial aviation. Acknowledging the uncertainty surrounding the economic effects of the pandemic, a series of COVID-19 traffic demand forecast scenarios were developed to represent a plausible range of recoveries for the aviation industry.

An initial step in the COVID-19 forecast process was the development of a series of guiding assumptions by the Forecasting and Economic Analysis Support Group (FESG) forecasting and aviation economics experts on how the industry would transition out of the abrupt initial downturn. These assumptions included: expectations by market type—passenger, cargo and business jet—for the duration of the initial downturn in demand; the short-run return to 2019, pre-pandemic, demand levels; anticipated timing of a COVID-19 vaccine announcement and availability for wide-spread use; and any potential longer-term effects, such as on business travel demand due to the pandemic related uptake in remote working and video conferencing.

For the COVID-19 forecast scenarios, the ICAO LTF model was updated with macroeconomic forecast information incorporating the anticipated economic effects of the pandemic. Available historical data was used to inform the decline in demand in 2020 along with assumptions and industry input used to calibrate the point at which each market is expected to return to their 2019 levels of activity, after which the updated LTF forecasts guide the longer-term trends.[3] Business jet forecasts were updated to incorporate the effects of COVID-19 in a similar manner.

The **passenger market** COVID-19 traffic demand scenarios show the sharp decline in 2020 due to the pandemic (estimated 68% decline in global revenue passenger kilometres (RPKs)) (Figure 1-1). The near-term recovery trajectories have global traffic demand returning to 2019 levels in 2023, 2024 and 2027 for the high, mid, and low scenarios, respectively. Over the 32-year forecast period, the COVID-19 mid forecast has revenue passenger kilometres growing at an annual average rate of 3.6% for both global and international demand (compared with 4.2% for global and 4.3% for international RPKs from the pre-COVID-19 LTF mid outlook).

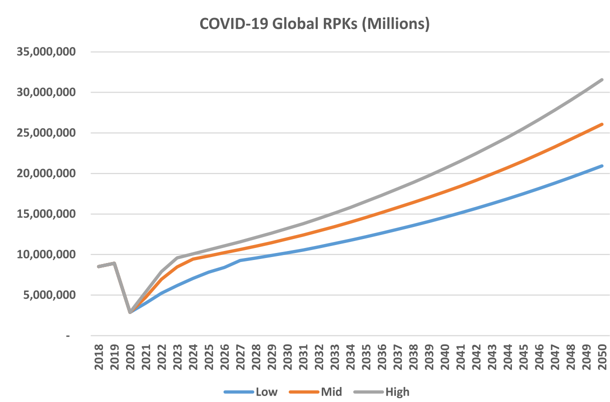


FIGURE 1-1: COVID-19 Global Passenger Forecast Scenarios

The **cargo market** COVID-19 forecast shows a decline in global demand of around 10% in 2020 with a return to 2019 levels by 2022 in the mid scenario (2021 in the high and 2023 in the low) (Figure 1-2). Over the course of the 32-year forecast global freight tonne kilometres (FTKs) are expected to grow by 3.5% per annum (unchanged from the pre-COVID-19 LTF outlook), with international FTKs increasing by 3.4% per annum (compared with 3.5% in the pre-COVID-19 outlook).

2 ICAO environmental trends assessment: https://www.icao.int/environmental-protection/Pages/Environmental-Trends.aspx
3 The ICAO COVID-19 LTF forecasts are published here: https://www.icao.int/sustainability/Pages/Post-Covid-Forecasts-Scenarios.aspx

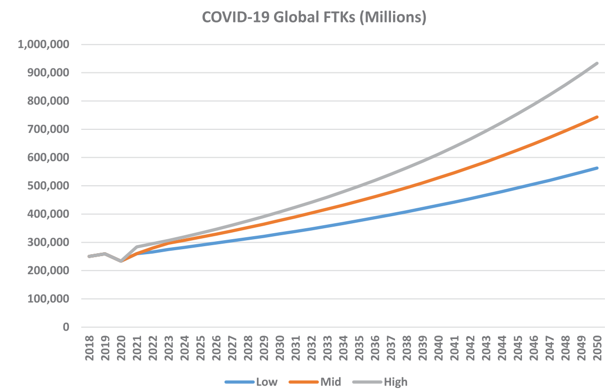


FIGURE 1-2: COVID-19 Global Cargo Forecast Scenarios

Business Jet operations experienced an estimated 21% decline in 2020 and are expected to return to 2019 levels in 2022, 2023 and 2024 for the high, mid, and low scenarios, respectively (Figure 1-3). Over the 32-year forecast period global operations are expected to register annual average growth at 2.7% for the mid outlook, compared with 2.9% for the pre-COVID-19 outlook.

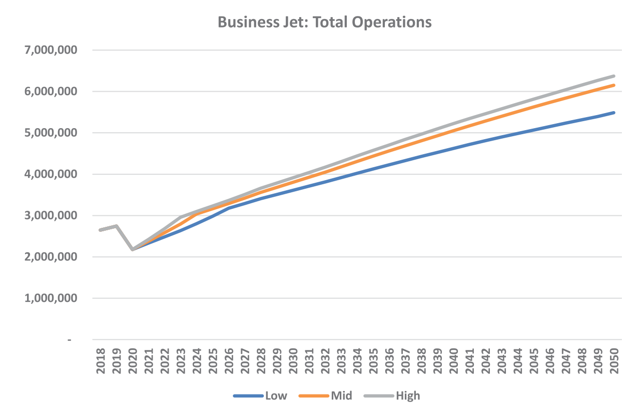


FIGURE 1-3: COVID-19 Global Business Jet Forecast Scenarios

Acknowledging the rapidly changing nature of the pandemic, at the end of CAEP/12 a qualitative review of the COVID-19 forecast scenarios was undertaken. The review concluded that the COVID-19 forecast scenarios used for trends remained reasonable when compared with more recent historical and forecast data. Over the near-term, and back to 2019 levels, the passenger RPK outlook was found to be broadly consistent with the International Air Transport Association (IATA) July 2021 forecast[4]. For cargo demand, while the actual recovery in FTKs outpaced the expected return to 2019 levels, the difference was not deemed significant.

Finally, a quicker than expected recovery in the business jet market suggested that the high forecast scenario may better align with actual data, but the possibility of a moderation in leisure travellers using business jets may slow the recovery path. However, this qualitative assessment did not consider the effects of the recent Ukrainian crisis, which will need to be undertaken as part of the CAEP/13 work cycle.

Trends in Emissions that Affect Global Climate

Table 1-1 below summarizes the aircraft technology and operational scenarios developed for the assessment of trends for fuel burn and aircraft emissions that affect the global climate. The CAEP/12 trends assessment included full-flight fuel consumption, carbon dioxide (CO_2), nitrogen oxides (NOx), and non-volatile particulate matter (nvPM).

Trends in Full-Flight Fuel Burn and CO_2 Emissions

Figure 1-4 shows results for full-flight (i.e., from departure gate to arrival gate) fuel burn for international aviation from 2005 to 2050. The analysis considered the impacts 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 aspirational goal were to be achieved.

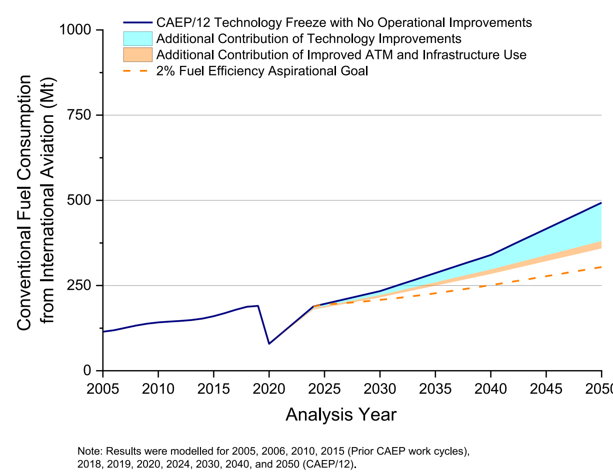


FIGURE 1-4: Fuel Burn from International Aviation, 2005 to 2050.

4 IATA provided FESG with data from their July 2021 forecast for the qualitative review.

Scenario	Aircraft Technology: Per annum fuel burn improvements for fleet entering after 2018	Aircraft Technology: Emissions Improvements against CAEP/7 IE NOx 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 CAEP/12 WG2 Conservative Operational Improvements	0.96 percent 2018 to 2050	NA	Migration to the latest operational initiatives (e.g., NextGen and SESAR) Fleet-wide CAEP/12 WG2 conservative operational improvements by route group
Fuel 3 - Advanced Aircraft Technology and CAEP/12 WG2 Medium Operational Improvements	1.16 percent 2018 to 2050	NA	Migration to the latest operational initiatives (e.g., NextGen and SESAR) Fleet-wide CAEP/12 WG2 medium operational improvements by route group
Fuel 4 - Independent Expert Integrated Review (IEIR) Technology and CAEP/12 WG2 High Operational Improvements	IEIR per annum (varies by aircraft type) 2018 to 2050	NA	Migration to the latest operational initiatives (e.g., NextGen and SESAR) Fleet-wide CAEP/12 WG2 high improvements by route group
NOx 1 - Technology Freeze with No Operational Improvements	NA: use only base year (2018) in-production aircraft	NA	NA: maintain current operational efficiency levels
NOx 2 - Moderate Aircraft Technology, CAEP/12 WG2 Medium Operational, and 50% CAEP/7 IE Emissions Improvements	Moderate aircraft technology improvements	50 percent of CAEP/7 IE NOx Goal met by 2036 with no further improvement thereafter	Fleet-wide CAEP/12 WG2 medium operational improvements by route group
NOx 3 - Advanced Aircraft Technology, CAEP/12 WG2 High Operational, and 100% CAEP/7 IE Emissions Improvements	Advanced aircraft technology improvements	100 percent of CAEP/7 IE NOx 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 - Technology Freeze with CAEP/12 WG2 High Operational Improvements	NA: use only base year (2018) in-production aircraft	NA	Fleet-wide CAEP/12 WG2 high operational improvements by route group

TABLE 1-1: Fuel Burn and GHG Emissions - Technology and Operational Improvement Scenarios.

For the year 2050, assuming Independent Expert Integrated Review (IEIR) technology with high operational improvements (Fuel Scenario 4), aircraft technology and operational improvements provide reductions in conventional fuel burn from international aviation of 113 million metric tonnes (Mt; 1kg x 10^9) and 22 Mt, respectively, for a total reduction of 135 Mt out of 493 Mt under technology freeze (Fuel Scenario 1). Similarly for global aviation, aircraft technology provides a reduction of 177 Mt and operations provides an additional reduction of 38 Mt, for a total of 215 Mt out of 793 Mt under the technology freeze scenario.

Even under the most aggressive CAEP/12 fuel burn technology improvements scenario (Fuel Scenario 4), the average fuel efficiency improvement (2015-2050) is 1.53% per annum. This efficiency improvement falls short of the ICAO's 2% aspirational goal for international aviation fuel burn but is slightly higher than the 1.37% per annum efficiency computed in CAEP/11 for the same time period. Overall, technology and operational improvements result in roughly a 27% reduction in fuel burn for both international and global aviation in 2050 for the CAEP/12 IEIR scenario (Fuel Scenario 4).

Figure 1-5 depicts the uncertainties associated with the forecasted demand, which is the largest contributor to uncertainty in fuel consumption. 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/12 forecast traffic trends are generally consistent with other published aviation forecasts. The forecast commercial market trend, which is for revenue tonne kilometres (RTK), shows a 20-year (2018-2038) compound average annual growth rate (CAGR) of 3.3%. By way of comparison, using revenue passenger kilometres (RPK) for all traffic as the forecast measurement, Boeing, Airbus and Embraer forecasts released in 2021 have 20-year (2019-2040) CAGRs of 4.0%, 3.9%, and 3.3%, respectively. The CAEP/12 RPK 20-year forecast (2018-2038) has a CAGR of 3.3%.

The delta between the CAEP/11 and CAEP/12 GHG trends baselines in 2040 is approximately 15%. Most of this variation can be attributed to differences between the central demand forecasts. Specifically, the CAEP/11 (2015) forecast was produced during a period of steady global economic growth with the expectation that this expansion would continue with global gross domestic product (GDP) growing at an annual rate of 2.8% over the ten years from 2015 to 2025 and 2.6% over the thirty-year period from 2015 to 2045. In contrast, the CAEP/12 forecast includes the effect of the COVID-19 pandemic both on the economic recovery path from 2020 and the long-term outlook and has a more tepid ten-year annual global GDP growth rate of 2.4% for 2018-2028 and 2.5% over the thirty-two-year period from 2018-2050.

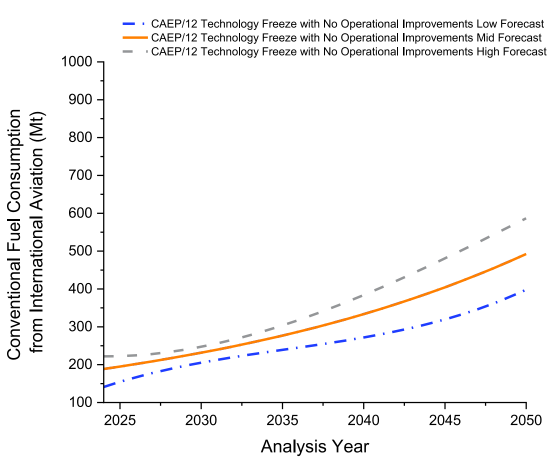


FIGURE 1-5: Range of Uncertainties Associated with Demand Forecast, 2024 to 2050.

Figure 1-6 presents full-flight CO_2 emissions for international aviation from 2005 to 2050; 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). Although not displayed here, the demand uncertainty effect on the fuel burn calculations shown in Figure 1-5 has a similar effect on the CO_2 results.

Considering the range of fuel consumption scenarios (Table 1-1), 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 532 Mt in 2050 compared to 2019 emissions.

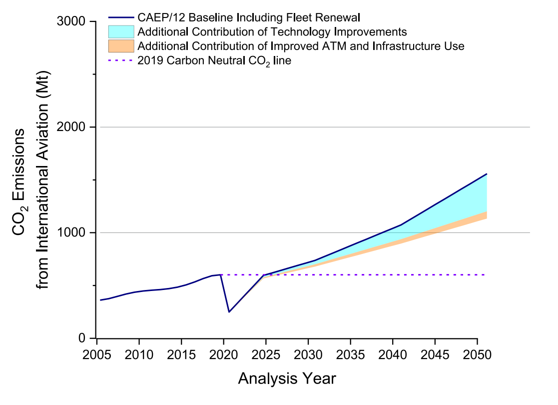
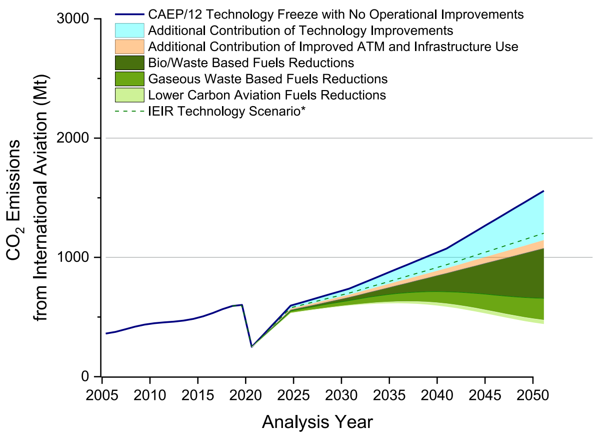


FIGURE 1-6: CO_2 Emissions from International Aviation, 2005 to 2050.

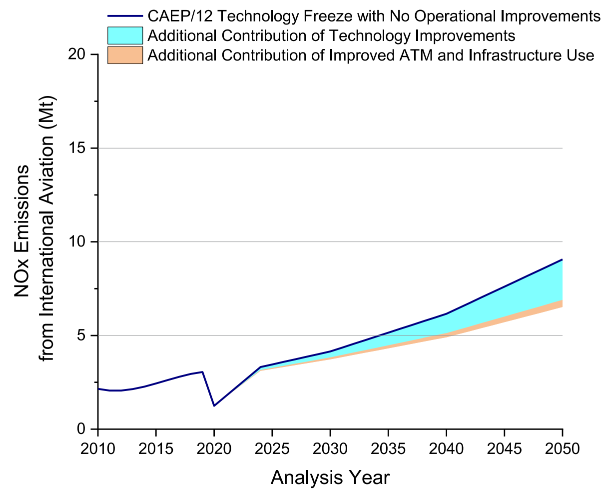
Contribution of Alternative Fuels to Fuel Consumption and CO_2 Trends

Figure 1-7 presents the net CO_2 emissions from international aviation, from 2005 to 2050, including alternative jet fuels lifecycle CO_2 emissions reductions. This portion of the CAEP/12 trends assessment work leveraged work undertaken by the CAEP Fuels Task Group (FTG), which conducted analyses to provide estimates of future bio- and waste-based sustainable aviation fuel (SAF-BIO/WASTE) production potential and associated lifecycle GHG impacts. It also drew from the Long-Term Aspirational Goal Task Group (LTAG-TG) analysis to extend SAF-BIO/WASTE projections and develop projections for additional SAF from waste CO_2 (SAF-CO_2) and for fossil-based lower-carbon aviation fuels (LCAF).



*Dashed line in technology contribution wedge represents the CAEP/11 Independent Expert Integrated Review (IEIR) Technology Scenario. **Note:** Results were modelled for 2005, 2006, 2010, 2015 (Prior CAEP work cycles), 2018, 2019, 2020, 2024, 2030, 2040, and 2050 (CAEP/12).

FIGURE 1-7: Net CO_2 Emissions from International Aviation, 2005 to 2050, Including Alternative Jet Fuels Lifecycle CO_2 Emissions Reductions (Based on 3.16 kg of CO_2 per 1 kg of fuel burn).



Note: Results were modelled for 2010, 2015 (Prior CAEP work cycles), 2018, 2020, 2024, 2030, 2040, and 2050 (CAEP/12)

FIGURE 1-8: Full-Flight NOx Emissions from International Aviation, 2010 to 2050.

The LTAG-TG developed three future fuels scenarios. Integrated Scenario 2 (IS2), which is approximately the mid-point of the three scenarios, was used for the CAEP/12 trends analysis. IS2 assumes faster rollout of future technology and operational efficiency and assumes that electrification of ground transport leads to increased availability of SAF. It also assumes that waste gases are widely used for SAF production, blue/green hydrogen is available for LCAF production, and carbon capture, utilization, and storage (CCUS) is in use. IS2 does not include the use of cryogenic hydrogen or atmospheric CO_2 via direct air capture (DAC).

Potential future production of LCAF and SAF-CO_2 were also estimated by the LTAG-TG for use in the trends analysis. SAF-CO_2 projections were based on waste CO_2 availability for high-purity sources (ammonia and ethanol production). Other sources including electricity, iron, steel, and cement production and DAC of CO_2 were assumed to be too costly. LCAF projections were based on fuel conversion technology availability to mitigate CO_2 emissions during LCAF production, including carbon capture, renewable hydrogen and energy use, avoiding venting and fugitives, and reducing flaring, as well as crude oil carbon intensity. The final values used in the trends assessment include total global production and an average Lifecycle Analysis (LCA) value for three fuel types (SAF-BIO/WASTE, SAF-CO_2, and LCAF). The LCA values were not intended to be applied separately to regional forecasts.

To calculate the “green wedges” in Figure 1-7, international market shares of each fuel type were applied to fuel demand volumes to generate CO_2 reductions from SAF-BIO/WASTE, SAF-CO_2, and LCAF. LTAG-TG provided fuel inputs for 2035 and 2050; for the purposes of the trends assessment, linear ramp-up functions were used to estimate adoption of these fuels between 2020 and 2035 and between 2035 and 2050, assuming replacement of 0% of total fuel demand in 2020 and 100% replacement in 2050. In addition to the 27% reduction in CO_2 emissions provided by technology and operational improvements in 2050, these fuels may provide an additional 56% reduction in net life-cycle CO_2 associated with international aviation (Fuel Scenario 4).

Depending on the SAF type, level of maturity and available technologies, the investment required to achieve the projected fuel volumes range from 6 b$ to 26 b$ per million tonnes of fuel per year (in 2020 US dollars). The cost abatement for implementing lower carbon technologies for LCAF production would be approximately $200/t$CO_2$ in 2050.

Trends in Full-Flight NOx and nvPM Emissions

Trends in full-flight NOx emissions from international aviation are shown in Figure 1-8. In 2018, NOx emissions were calculated as 2.94 Mt. In 2050, NOx emissions range from 6.50 Mt under Scenario 3 to 9.06 Mt under Scenario 1, representing up to a 2.56 Mt (4.06 Mt for global aviation) reduction with technology and operational improvements.

Figure 1-9 shows trends in nvPM mass emissions from international aviation. Operational improvements (nvPM Scenario 2) are expected to result in 465 tonnes and 895 tonnes reduction of nvPM mass emissions for international and global aviation, respectively. This amounts to a roughly 5% reduction from the baseline (nvPM Scenario 1).

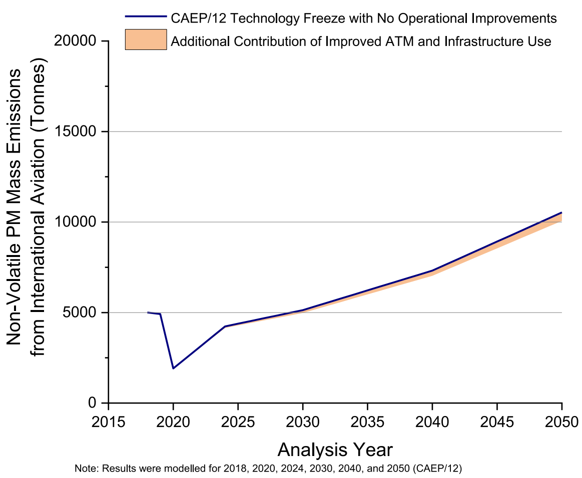


FIGURE 1-9: Full-Flight nvPM Mass Emissions from International Aviation, 2018 to 2050.

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 (55, 60, and 65 dB) for 319 global airports, representing approximately 80% of the global traffic. 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 (GPW v4) was used.

Scenario 1 (CAEP/12 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 2050. Scenario 3 was meant to capture a COVID-19 delay, with no noise technology improvements for aircraft entering the fleet from 2019 to 2023, and technology improvements of 0.2 EPNdB per annum for all aircraft entering the fleet from 2024 to 2050. Scenario 4 includes noise technology improvements of 0.2 EPNdB per annum for all aircraft entering the fleet from 2019 to 2050. For Scenarios 2, 3, and 4, an additional moderate operational improvement of 2% is applied for population inside DNL 55, 60, and 65 contours.

Figure 1-10 provides results for the total global 55 DNL contour area (i.e., for 319 airports) for 2018, 2019, 2020, 2024, 2028, 2038 and 2050 for the four scenarios. Historical data modelled in the prior CAEP/11 work cycle is also shown for 2015. The 2018 contour area is 16,486 square-km. This value decreases to 9,451 square-km in 2020 due to the COVID-19 downturn and increases to 15,530 square-km by 2024. In 2050 the technology freeze (Scenario 1) total global contour area is 31,407 square-km and decreases to 15,196 square-km and 21,570 square-km, with advanced and low technology improvements, respectively. The total population inside the 55 DNL contours was estimated to 37 million in 2018 and could range from 76 million under Scenario 1 to 38 million under Scenario 4 in 2050; this is under the assumption that population density around airports does not vary in time.

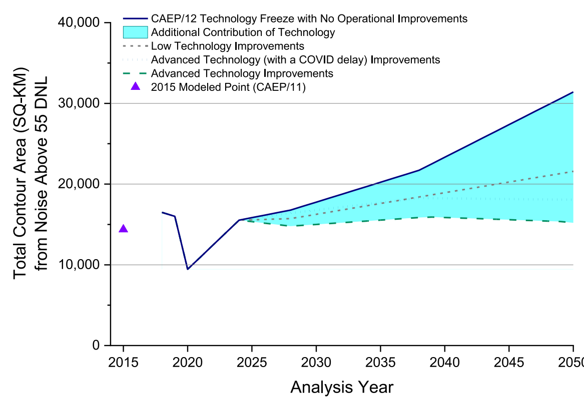


FIGURE 1-10: Total Aircraft Noise Contour Area Above 55 dB DNL for 319 Airports (km^2), 2015 to 2050

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 NOx and total (volatile and non-volatile) particulate matter (PM). The NOx and PM scenarios for LTO are equivalent to those used in the full-flight trends assessment (Table 1-1).

NOx emissions below 3000 feet from international aviation are shown in Figure 1-11. In 2050, technology improvements are expected to provide up to 0.17 and 0.38 Mt of reductions in NOx emissions for international and global aviation, respectively. Operational improvements are smaller than those that could be realized by technology, namely additional reductions of up to 0.03 and 0.08 Mt in 2050 for international and global aviation, respectively.

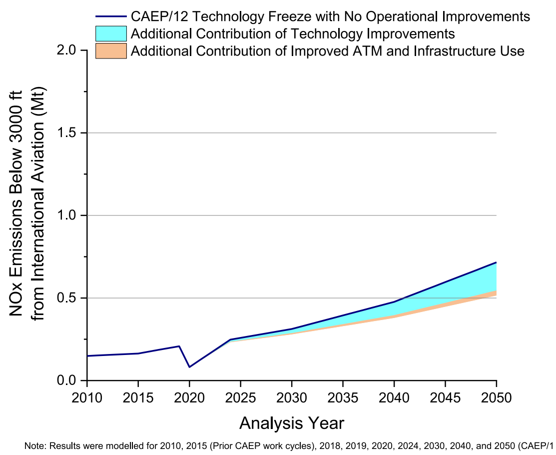


FIGURE 1-11: NOx Emissions below 3,000 Feet - International Aviation, 2010 to 2050.

Non-volatile PM emissions below 3000 feet from international aviation are shown in Figure 1-12. In 2050, operational improvements may provide additional reductions in nvPM emissions of up to 50 tonnes and 140 tonnes for international and global aviation, respectively (about 5% reduction). Total PM below 3000 feet from international aviation were estimated to 1360 tonnes in 2018 and could range from 3220 tonnes to 3070 tonnes in 2050.

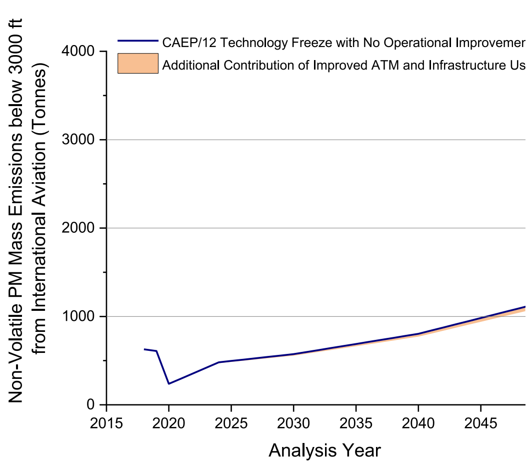


FIGURE 1-12: Non-volatile PM Emissions Below 3,000 feet —International Aviation, 2018 to 2050.

Conclusion

Full-flight and LTO emissions from international aviation are expected to increase through 2050 by 2 to 4 times 2018 levels, depending on the pollutant (CO_2, NOx, nvPM, or PM) and the analysis scenario. Specifically for the full flight technology freeze scenario (Fuel Scenario 1), CO_2, NOx, and nvPM are expected to increase by a factor of 2.6, 3.2 and 2.0, respectively. For LTO emissions (Fuel Scenario 1), NOx, PM and nvPM are expected to increase by a factor of 3.8, 2.4 and 1.8, respectively. These factors are generally consistent for both international and global aviation. The total DNL 55 noise contour area at the 319 airports in the analysis could stabilize after 2025 under an advanced technology improvements scenario.

In 2018, international aviation consumed approximately 188 Mt of fuel, resulting in 593 Mt of CO_2 emissions. By 2050, fuel consumption is projected to increase 1.9 to 2.6 times the 2018 value, while revenue tonne kilometres (RTK) are expected to increase 3 times under the most recent forecasts (the 32-year [2018-2050] compound annual growth rate for RTKs is 3.5%). 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 1.53% per annum (2015-2050). 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.

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