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Recent and Projected Trends in Global Civil Aviation NO_x Emission Indices

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Aircraft emitted oxides of nitrogen (NO_x) contribute both to climate change and air quality degradation. The trend of higher gas temperatures, caused by engine design choices seeking lower fuel consumption and achieve more complete combustion, has the adverse effect of increasing NO_x formation, which might however be compensated by improved combustor designs. The tradeoff between lowering NO_x or CO_2 emissions is an important consideration in mitigating the environmental impacts of aviation, and, and in context of the industry's environmental targets and forecasts, quantifying the technological trend taking place can provide an indication of future emission totals. In this study, we estimate bottom-up global fleet average aviation fuel burn and NO_x emissions for the years 2005 and 2018 and extrapolate their totals to 2030, 2040, and 2045 with current air traffic and engine performance forecasts. Average NO_x emission indices are evaluated for different aircraft classes at each year considered, and their changes over time are discussed together with a sensitivity analysis on the assumptions made.

I. Nomenclature

ASK	=	available seat kilometers
c	=	RPK-specific fuel consumption, kg/RPK
EI	=	emission index, g/kg
F	=	mass of fuel burned, kg
k_{op}	=	percentage reduction in fuel consumption due to operational improvements
k_{tec}	=	percentage reduction in fuel consumption due to aircraft technology improvements
NO_x	=	oxides of nitrogen, mass reported as equivalent kg of NO_2
r	=	compound annual growth rate
ret	=	fraction of fleet that retired

Subscripts

class	=	specific to aircraft class
i	=	specific to aircraft type
new	=	aircraft entering the fleet in the current year
old	=	aircraft already present in the fleet
rgn	=	specific to regional origin-destination pair
y	=	at year y

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II. Background

Emissions of oxides of nitrogen (NO_x) are the main contributors to the air quality impacts associated with aviation [1–3], and play a significant role in aviation's climate impact [4]. The social cost of air quality impacts have been found to be a significant component of the overall environmental damage from aviation [5], particularly having a comparable magnitude to the social costs associated with climate impacts if the effects of cruise emissions on air quality are considered [6]. Based on aviation activity in 2015, Grobler et al. [6] estimate the marginal environmental cost of a metric ton of fuel burn to be $560 [180-1,400, 90% CI]. Of this environmental cost, $140 [21-360, 90% CI] is attributable to CO_2 climate impacts and $330 [38-1,100, 90% CI] is attributable to aggregate air quality and climate NO_x impacts. If the full environmental impacts of aviation are to be addressed, design and policy decisions have to consider the air quality degradation associated with non-CO_2 emissions in addition to their short-term and long-term climate forcing.

Despite technological improvements, it is expected that the growth of civil aviation will cause the amount of NO_x emissions to increase between the years 2005 and 2050 [7,8]. Reducing these emissions and their associated environmental effects is complicated by the existence of tradeoffs in engine design, in which higher pressure ratios and turbine inlet temperatures are beneficial in terms of thermodynamic efficiency, specific thrust, and combustion completeness, but detrimental in terms of increasing NO_x formation [9,10]. The trend in turbofan design of higher overall pressure ratios leads to decreased fuel consumption, which is both economically desirable and reduces CO_2 emissions along with their associated climate impacts [11]. Some studies have analyzed the tradeoff between CO_2 and NO_x emission reductions, suggesting that regulating aviation NO_x to more stringent values might have an overall detrimental effect on climate change due to the incurred loss of fuel efficiency [8,12].

NO_x emissions during landing and takeoff operations (LTO) are regulated for the turbofan engines used in airliners by the International Civil Aviation Organization (ICAO), with limits on emitted mass per thrust increasing according to the engine's overall pressure ratio [13]. After their adoption in 1981, these limits have been tightened in 1993, 1999, and 2005, with new requirements coming into effect some years after each new standard was accepted. Parallel to that, new combustor technologies have been implemented to meet emission requirements while seeking overall lower fuel consumption. ICAO's first standard setting minima for aircraft fuel efficiency took effect for new designs in 2020 and will be applied to all newly built aircraft from 2028 [14]. However, the fact that multiple currently sold aircraft already meet this standard has led to arguments that the standard's impact will be mild [15]. The combined effects of lower fuel consumption and higher NO_x emission indices (EI, defined as mass emitted per mass of fuel burned) caused by higher pressure ratios have led to relatively stable levels of NO_x per passenger seat-km in that period [11]. With this trend not expected to change significantly, total NO_x emissions are forecast to increase in the next three decades, following the growth of civil aviation, according to ICAO's Committee on Aviation Environmental Protection (CAEP) [7].

In this study, we provide further insight into these trends by estimating the annual global fleet average fuel burn and NO_x emission indices for different aircraft classes in the years 2005 and 2018 using flight schedule data and a spatially resolved model simulating aircraft performance to estimate fuel burn and emissions, with a bottom-up approach. Emissions are also scaled up to the year 2050 using existing projections of technological advancements and aviation activity. These estimates show how aviation NO_x and CO_2 emissions changed over time for each aircraft class and how they are expected to change in the coming decades.

III. Methods

A. Estimating realized global aircraft emissions

An emissions inventory for each analyzed year (2005 and 2018) is created by first producing a comprehensive list of any civil aviation flights that occurred, then estimating each flight's emissions using the methods described here, and finally aggregating those emissions as needed for analysis.

Flight schedule data compiled by the company OAG is used to create a list of global flight movements for the entirety of the years 2005 and 2018. The emissions for each combination of aircraft type, origin, and destination in each month are simulated with the openAVEM model, further described in Ref. [16]. LTO emissions are calculated with time-in-mode values proposed by Stettler et al. [17]. The non-LTO portion of each flight is simulated with the BADA 3.15 aircraft performance model, which uses a total energy formulation of aircraft kinetics [18]. Flights follow a geodesic trajectory with a constant aircraft type dependent cruise flight level. Wind speeds are applied using monthly average values of the MERRA-2 reanalysis product from the Global Modeling and Assimilation Office (GMAO) at NASA Goddard Space Flight Center. Non-LTO emissions are calculated using the Boeing Fuel Flow Method 2 [19,20], and CO_2 emissions are calculated using the constant EI of 3155 g/kg as used in the U.S. Federal Aviation

Administration's emissions model [21]. To account for the actual distance flown, the non-LTO emissions are multiplied by a lateral inefficiency factor equal to 1.0387 plus the equivalent of additional 40.5 NM to the great circle distance, based on Seymour et al. [22].

Engine emission indices at certification operation points are taken from the ICAO Engine Emission Databank for turbofans [23], and the U.S. Environmental Protection Agency for turboprops and older turbofans [24]. Airport properties are sourced from the OpenFlights and OurAirports databases [25,26].

Aircraft types are grouped into the classes of twin aisle, single aisle, regional jet, and turboprop based on form and engine type. Emissions from business jets and piston engine aircraft, which are estimated to contribute to 1% of global fuel burn [16], are not included in this analysis due to unscheduled flight movement data not being available. Emissions from cargo flights are calculated, but they are excluded from the analysis of future emissions, which is limited to passenger flights. We disregard engine degradation and assign a single specific engine model for each aircraft type instead of considering all engine options.

B. Projecting aircraft fuel burn and emissions towards 2050

For the four aircraft classes mentioned, projections are calculated up to the year 2050 by considering the engine fuel burn and NO_x emission goals identified by ICAO's 2017 independent expert integrated review panel [27] and ICAO's long-term passenger traffic forecast [28,29]. The emission goals defined by the expert panel relate to engines which enter into service by the target dates of 2027 and 2037. In this study, we assume the use of conventional (fossil-based) jet fuel, and model future engine performance as a continuous improvement, with piecewise linear interpolation between those goal points, extrapolating improvements from 2037 to 2050. Transformative engine or aircraft technologies, such as electric or hydrogen propulsion, beyond those considered relevant until 2037 by the panel, are not contemplated in the analysis. Figure 1 gives an overview of how the emission projections are produced, with the relevant factors listed being described in more detail further in this section.

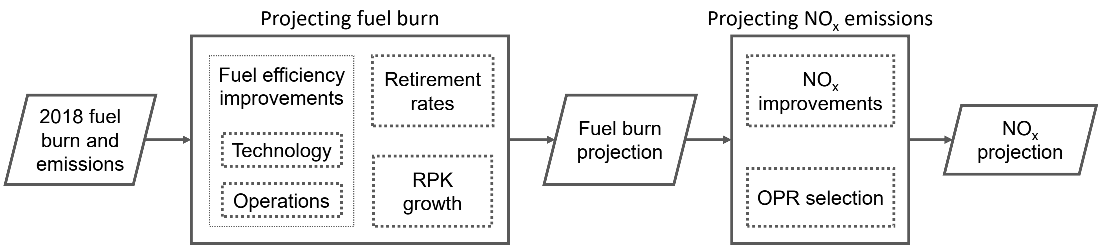


Figure 1 Overview of the process of projecting 2018 fuel burn and NOx emissions.

Air traffic is modeled by considering the revenue passenger-km (RPK) achieved by each aircraft type for each pair of origin and destination world regions. Flights are grouped according to the regional definitions used in the ICAO's long-term traffic forecast. The OAG schedule data includes available seats for each flight, allowing for the calculation of total available seat-km (ASK) for each aircraft type and regional pair. A global average passenger load factor of 81.7% is then estimated from the ratio of total ASK and the global RPK value published by ICAO [30]. This load factor is applied equally to all aircraft type and region combinations to estimate specific RPK values for 2018.

The 2018 RPK values are projected by applying the regional-pair specific compound annual growth rates ($r_{y,rgn}$) from the ICAO's long-term forecast (Eq. 1). Four forecast scenarios are considered: the medium traffic projection made prior to the COVID-19 pandemic (*Pre-COVID*) [28], and three projections made in July 2021 with different levels of recovery and growth (*High*, *Mid*, *Low*) [29]. Constant growth rates are given for the periods from 2018 to 2028, 2038, and 2048 (or 2050 for the post-COVID scenarios). For the three post-COVID cases, we apply the pre-COVID forecast between 2018 and 2019, and consider zero RPK growth between 2019 and 2023 (High), 2024 (Mid), or 2027 (Low), with growth resuming at a pace that matches the forecast traffic for 2028 in each scenario. Since ICAO's air-traffic forecasts concern only total passenger and cargo traffic and there is no consensus on how this new demand will be spread in the various segments of the aircraft market, we consider that the proportion of aircraft in each class is constant from 2018 onwards (Eq. 2).

$$RPK_{y,rgn} = r_{y-1,rgn} \cdot RPK_{y-1,rgn} \tag{1}$$

$$RPK_{y,class} = RPK_y \cdot RPK_{y=2018,class} / RPK_{y=2018} \tag{2}$$

At each year, the projected traffic demand is met by a combination of aircraft that were already operating and aircraft introduced that year (Eq. 3). The traffic realized by already existing aircraft is calculated as the same as the previous year scaled to the expected fraction of aircraft that remain in service (Eq. 4). A generic aircraft of each class, with up-to-date performance, is introduced every year to make up the difference between the total RPK projected and the RPK achieved by the already operating aircraft that remain operating (Eq. 5).

$$RPK_y = \left(\sum RPK_{y,i}\right)_{old} + \left(\sum RPK_{y,class}\right)_{new} \tag{3}$$

$$RPK_{y,i,old} = RPK_{y-1,i,old} \cdot (1 - ret_i) \tag{4}$$

$$RPK_{y,class,new} = RPK_{y,class} - \left(\sum RPK_{y,i,old}\right)_{class} \tag{5}$$

Fleet renewal is modeled by applying, each year, a class-specific retirement rate to the current age distribution of each aircraft type, yielding the fraction of the type's fleet that retired at that year (ret_i). Retirement rates are modeled as a logistic function using the parameters given by Ref. [31], which have median retirement ages of 27.7, 28.9, 29.5, and 33.2 years for twin aisle, single aisle, regional jet, and turboprop classes respectively. The initial aircraft age distribution (for 2018) is primarily estimated by applying the retirement model to historic annual delivery numbers from Boeing, Airbus, Embraer, and Bombardier. Additionaly the initial ages of some aircraft types are estimated based on the entries present in the national aircraft registries of the US, Brazil, and Spain. If age data for a type is still insufficient, online crowdsources aircraft databases (such as planespotters.net) are used or a constant delivery rate during the years of production is assumed.

Fuel consumption (c_y) is quantified for each aircraft type by the ratio between fuel burn and RPK (Eq. 6). These values are calculated globally, as some aircraft types might fly only a low number of routes for a given pair of regions which might not be representative of the aircraft performance if the routes were to change within the same regional pair. The RPK-specific fuel consumption values calculated for 2018 are then scaled every year by the expected average reduction due to operational improvements (k_{op}) according to the goals set in 2010 by a panel of independent experts under the ICAO CAEP [32]. The specific fuel consumption of newly introduced aircraft are also adjusted by a factor to account for technological improvements (k_{tec}) (Eq. 7).

$$c_y = F_y / RPK_y \tag{6}$$

$$\begin{cases} c_{y,i,old} = c_{y-1,i,old} \cdot \left(1 - k_{op,y-1}\right) \\ c_{y,class,new} = c_{y-1,class,new} \cdot \left(1 - k_{op,y-1}\right) \cdot \left(1 - k_{tec,y-1}\right) \end{cases} \tag{7}$$

A similar procedure is followed for estimating the NO_x emissions given a specific NO_x technology improvement. Specifically, the NO_x emission goals as stated in ICAO's 2017 independent expert integrated review panel [27] are expressed in terms of improvements to the ICAO CAEP NO_x standards. These are a function of the engine's OPR, and as a result OPR future estimates are used in calculating the resulting NO_x emissions from the estimated fuel burn. We consider that OPR increases constantly up to the values of 60, 65, and 70 in 2027 for regional jets, narrowbodies, and widebodies, respectively. For turboprop aircraft, we do not assume any NO_x technological improvements or changes in pressure ratio. To capture a variety of scenarios and estimate the sensitivity, we assess the resulting NO_x emissions of a range of potential future OPR values, for each aircraft class. While the OPR value affects the NO_x emissions, it also impacts the overall engine efficiency, and thus the resulting fuel burn. We note that we do not capture this later effect in this modeling chain, and that we solely represent aircraft and engine technological improvements in terms of the overall fuel efficiency technology targets as stated in ICAO's 2017 independent expert integrated review panel [27]. We do not anticipate this mismatch to be introducing significant uncertainty in the estimated EIs, but future work could focus on propagating these OPR ranges also to fuel efficiency improvement estimates.

Finally, we quantify the sensitivity of different modeling variables (listed in Table 4) to the estimated fuel burn, NO_x emissions, and forecasted EI(NO_x). The ranges of values for the operations and the technological fuel consumption reductions assumed are included in Table 4 in the Appendix.

Table 1 Scenarios considered in the sensitivity analysis to the different modeling parameters. Configurations in italics are used in the baseline forecast.

Variable	Scenarios			
RPK growth	Pre-COVID	Low	*Mid*	High
Fuel consumption improvement from technology	Low	*Moderate*	Advanced	Optimistic
Fuel consumption improvement from operations	Low	*Baseline*		
Aircraft retirement	Slow	*Baseline*	Fast	
NOx technology improvement	*Baseline*	Continued-low	Continued-high	
Pressure ratio	No change	Low to 2027	*High to 2027*	High to 2037

IV. Results and discussion

We first present the near-present-day (2018) fuel burn and emissions and compare them to 2005 to quantify the recent (pre-COVID-19) growth in aviation. We then provide the estimates for the evolution of fuel burn and NO_x emissions under the four forecast scenarios, and quantify their sensitivity to the various modeling assumptions.

A. Aircraft fuel burn and NO_x emissions in 2005 and 2018

As a first step, emissions were calculated for 2005 and 2018, for which flight movement data is available. The global averages obtained for passenger traffic for 2005 and 2018 using this approach are presented in Table 2.

Table 2 Global fuel burn and average NO_x emission index ($EI(NO_x)$) in 2005 and 2018 per aircraft class. For 2018 the RPKs and the fuel burn from both passenger and cargo operations is also presented.

	Fuel burn [Tg] (% of total)			RPK [10^9]	$EI(NO_x)$ [g/kg]		
Aircraft class	2005	2018	2018 w/ cargo	2018	2005	2018	2018 w/ cargo
Twin aisle	94.8 (53.4%)	125.7 (47.6%)	140.8 (50.3%)	3634	16.0	18.5	18.2
Single aisle	68.3 (38.4%)	121.4 (46.0%)	122.2 (43.7%)	4289	11.9	12.5	12.5
Regional jet	11.3 (6.3%)	13.2 (5.0%)	13.2 (4.7%)	280	10.5	11.3	11.3
Turboprop	3.3 (1.9%)	3.6 (1.4%)	3.6 (1.3%)	74	9.3	9.3	9.3
Total	177.7	264.0	279.9	8278	14.0	15.3	15.3

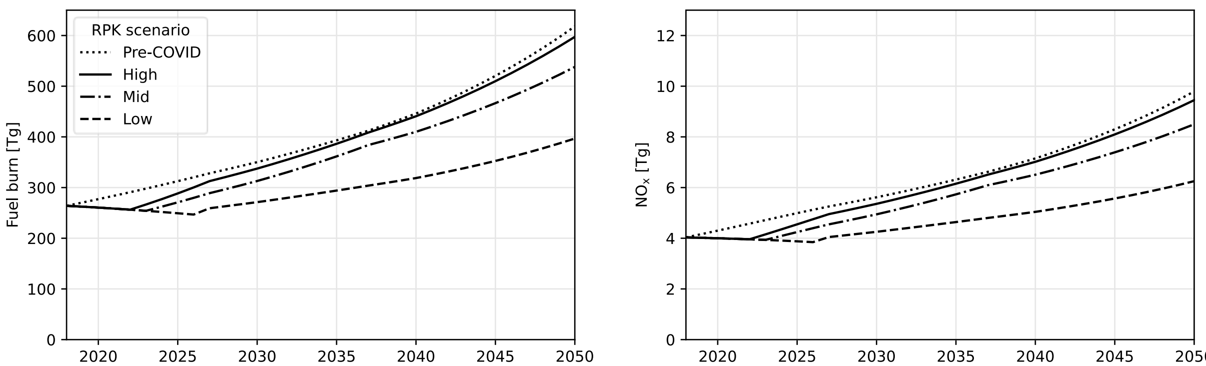
The resulting total (passenger and cargo) fuel burn for 2018 is 280 Tg which is comparable to other estimates – it is 9% higher than the 2018 fuel burn estimate by Seymour et al. [22] and 2% lower than the estimate by Graver et al. [33]. This work focuses on passenger aircraft operations, which result in 264 Tg of fuel burn in 2018. and thus constitute the majority of aviation emissions. Nevertheless, for comparison purposes the fuel burn from both passenger and cargo operations for 2018 is also included in Table 2. Cargo operations contribute to ~6% of global aviation fuel burn, primarily from twin aisle aircraft.

For 2005, we estimate 177.7 Tg of fuel burn from passenger aircraft, indicating a 48.5% increase between 2005 and 2018. In both years this fuel burn is primarily used by twin and single aisle aircraft, with regional jets and turboprops responsible for 6.4-8.2% of fuel burn. The fuel burn per RPK is ~20% higher for twin aisle compared to single aisle aircraft given their longer range.

NO_x emissions in 2018 totaled 4.28 Tg (base NO_2), yielding a global fleet average NO_x EI of 15.3 g/kg in that year. This EI for 2018 is 9% higher than the one for 2005 (14.0 g/kg), which is in agreement with the observed trend of increasing NO_x EI and improved fuel efficiency over time. Twin aisle aircraft have a higher global fleet average NO_x EI, which has increased three times faster than the one of single-aisle aircraft, from 16 g/kg in 2005 to 18.5 g/kg in 2018. With the currently estimated environmental cost of NO_x being ~2.3 times that of CO_2 for every tonne of fuel burn [6], this increasing trend in the EI of NO_x can lead to significant atmospheric impacts, and is one of the reasons that further motivate this work.

B. Future fuel burn and NO_x emissions under different scenarios

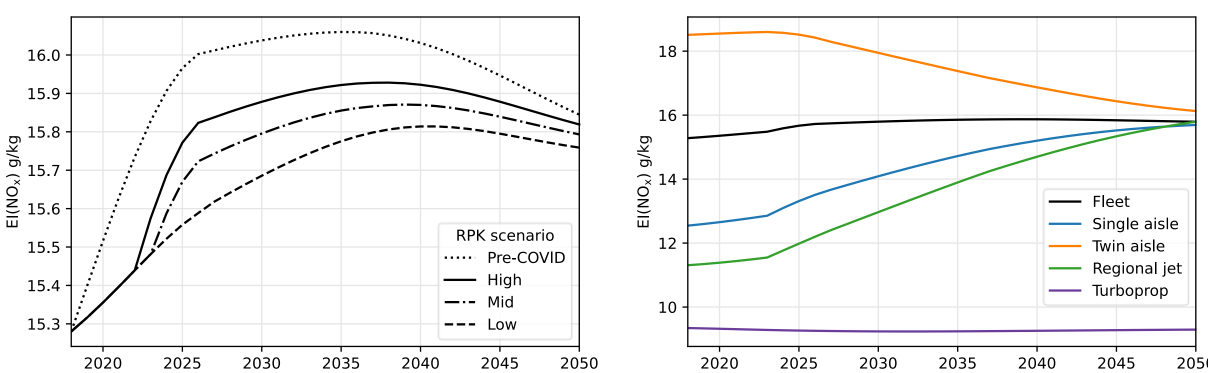
Figure 2 presents the projected fuel burn and NO_x emissions from 2018 to 2050 for different air traffic growth scenarios. In all cases fuel burn and the resulting NO_x emissions grow by 2050. The annual fuel burn grows by 50-134%, and the annual NO_x emissions by 55-143%, depending on the air traffic growth scenario. We note that the recent and current effects of the COVID-19 related reductions in emissions are not represented in the short-term, as e.g. in 2020 significantly lower fuel burn and emissions were observed than displayed in Figure 2 [16]. This is an artifact of the RPK scenarios which capture the average growth between 2018 and 2028, which we do not distribute between the years in high fidelity as we are interested in longer timelines (see Methods).



(a) (b)

Figure 2 Annual fuel burn (a) and NOx emissions (b) projections for the four air traffic (RPK) growth scenarios.

The projected variation of $EI(NO_x)$ over time is shown in Figure 3 for the four different air traffic growth scenarios (a) and how it varies between the aircraft classes (b). Driven by the underlying modeling assumptions, all air traffic growth scenarios result in a similar $EI(NO_x)$ at 2050, ranging between 15.75-15.85 g/kg, i.e. a ~3% further increase compared to 2018. However, depending on the air traffic growth rate, and thus the need for new aircraft at different rates, the high RPK scenario has a higher fleet average $EI(NO_x)$ in the first two decades. This is a result of the fact that the EIs of the reference aircraft assumed have higher $EI(NO_x)$ than the 2018 global fleet average, thus resulting in higher EIs when they enter the fleet, before the effect of the NO_x technology goals becomes apparent. In terms of the different aircraft classes, the single aisle and twin aisle aircraft, which form the majority of traffic and thus emissions, show a similar trend, with the widebody aircraft by exhibiting the largest eventual reductions of $EI(NO_x)$ in 2050, compared to 2018.



(a) (b)

Figure 3: Projected evolution of $EI(NO_x)$. (a) presents the global fleet average $EI(NO_x)$ for the four air traffic (RPK) growth scenarios. (b) presents the fleet average $EI(NO_x)$ for the different classes for the 'Mid' RPK scenario.

The spatial distribution of the projected NO_x emissions is heterogeneous, driven by the underlying varying air traffic growth rates between the different regions. For the mid growth scenario, while the NO_x emissions from flights departing from Europe and North America are expected to grow by ~65-74% between 2018 and 2050, NO_x emissions from flights departing from the remaining regions are expected to grow by ~147% in total. We note that both in 2018 and 2050 the highest NO_x emissions are attributed to air traffic departing from Europe.

C. Sensitivity of future fuel burn and NO_x emissions to different forecast parameters

Table 3 presents the relative changes in the aggregate fuel burn and NO_x emissions over the period of 2018 through 2050 that different individual modeling choices result in, in order to both assess the sensitivity of our results to the specific assumptions made and to demonstrate the high variability that the provided estimates have. Estimates for the time averaged EI(NO_x) over the whole period and the EI(NO_x) at 2050 are also provided, for the same reasons.

Overall, individual scenario choices can result in total fuel burn variations of -17.3%-9%, total NO_x emissions variations of -17.7%-38.7%, and the time-averaged EI(NO_x) and the EI(NO_x) in 2050 varying by -19.2%-+38.7% and -32.2%-66.6%, respectively. The optimistic fuel efficiency improvements result in a 5% decrease in fuel burn and emissions, and the most extreme aircraft retirement scenario replacement (annual, for demonstration purposes only) can reduce the aggregate fuel burn by up to ~15%.

The largest variations are introduced by the NO_x technology and OPR scenario selection in the NO_x estimation process. The OPR scenarios assumed for the different aircraft classes, and result in large variations in the EI(NOx), which could partially be driven by the mismatch in the OPR assumptions in the fuel efficiency and NO_x calculations.

Table 3: Effects of different modeling parameter choices on the total fuel burn and NO_x emissions between 2018 and 2050, as well as the estimated global fleet average EI(NO_x) averaged over the 2018-2050 and the estimated global fleet average EI(NO_x) for 2050. Descriptions of the different scenarios are provided in the Methods section.

Scenarios	Fuel burn	NO_x	Avg. EI (NO_x)	EI(NO_x) in 2050
RPK				
pre-COVID	+10.9%	+12.1%	+1.1%	+0.3%
Low	-17.3%	-17.7%	-0.5%	-0.2%
Mid	+0.0%	+0.0%	+0.0%	+0.0%
High	+7.3%	+7.7%	+0.4%	+0.2%
Retirement				
Baseline	+0.0%	+0.0%	+0.0%	+0.0%
Fast	-4.6%	-4.0%	+0.7%	-0.2%
Slow	+4.4%	+3.7%	-0.7%	+0.0%
Fuel burn technology				
No change*	+10.0%	+10.0%	+0.0%	-0.0%
IE	-1.9%	-2.0%	-0.1%	-0.2%
Low	+3.8%	+3.9%	+0.0%	-0.0%
Moderate	+0.0%	+0.0%	+0.0%	+0.0%
Advanced	-1.9%	-1.9%	-0.0%	+0.0%
Optimistic	-4.9%	-4.9%	-0.0%	+0.0%
Operations				
Baseline	+0.0%	+0.0%	+0.0%	+0.0%
Low	+2.0%	+2.0%	+0.0%	-0.0%
No change*	+5.3%	+5.3%	+0.0%	-0.0%
NO_x technology				
Baseline	+0.0%	+0.0%	+0.0%	+0.0%
Continued-conservative	+0.0%	-3.1%	-3.1%	-7.3%
Continued-optimistic	+0.0%	-9.8%	-9.8%	-27.7%
No change*	+0.0%	+38.7%	+38.7%	+66.6%

OPR (for NO_x only)				
Baseline	+0.0%	+0.0%	+0.0%	+0.0%
Low to 2027	+0.0%	-4.3%	-4.3%	-3.4%
IE	+0.0%	-9.3%	-9.3%	-14.4%
No change*	+0.0%	-19.2%	-19.2%	-32.2%

*No change from the reference aircraft

We note that we have not examined simultaneous changes in the modeling assumptions, which could further expand the variations in the estimates provided. Future work could introduce probability distributions for the values of the different scenario variables presented here and follow a Monte Carlo approach to assess the resulting uncertainties in the fuel burn and emissions estimates.

V. Conclusions

In this work we assess the recent and projected trends in global aviation fuel burn and NO_x emissions. Between 2005 and 2018, we find that aviation fuel burn (and thus CO_2 emissions) have increased by ~50%, and that the growth in NO_x emissions has surpassed that of CO_2, resulting in a global fleet average EI of NO_x increase by ~9% between the two years. This is in agreement with observed trends resulting from 'allowing' higher NO_x emissions for obtaining further fuel efficiency improvements.

With the increasing understanding of the environmental impacts of aviation emissions, NO_x emissions are increasingly developing to be a key contributor to aviation's atmospheric impacts. Despite the higher uncertainty ranges and lower level of scientific understanding compared that to the effects of CO_2 [4,6], NO_x emissions from aviation are presently estimated to lead to higher environmental externalities than CO_2 emissions, primarily driven by the air quality impacts associated with emissions. With the multiple international, regional and national targets in the coming decades for addressing aviation's environmental impact, forecasts of potential future emissions are critical. In contrast with CO_2 impacts, which scale linearly with fuel burn, NO_x emissions partake in multiple non-linear chemistry processes, resulting in the same amounts of NO_x emissions leading to different air quality and climate impacts depending on the location they are emitted and the background level of atmospheric composition (driven by other sectors' emissions, among other factors) [8,12,34,35]. As a result forecasts are needed not just in terms of emissions totals, but also in terms of their spatiotemporal distribution in the global domain over time.

To aid such analyses and to provide insight on the potential future developments in the fuel efficiency versus EI NO_x engineering tradeoffs, we use existing passenger traffic as well as technological and operational improvements targets to forecast global aviation fuel burn and NO_x emissions through 2050. While we do not capture the short-term effects of COVID-19 restrictions, these are included in the RPK scenarios used, and are thus reflected in the longer-term estimates provided. In all scenarios aviation fuel burn and the associated NO_x emissions continue to increase. We find that based on these targets the global fleet average EI(NO_x) will further increase by ~ 3% by 2050, despite its 9% growth between 2005 and 2018. The 'slowing down' of the EI(NO_x) growth trend indicates either the shifting focus of the OEMs towards reducing NO_x emissions through the introduction of new technologies that do not substantially impact the fuel efficiency or the potential optimistic character of these non-binding targets that are assumed in this work. Future work could focus on coupling the modeling assumptions between the fuel efficiency estimates and NO_x improvements, and on uncertainty quantification of the modeling parameters which can complement these findings and can further increase the robustness of the sensitivity analysis presented here. Finally, as the COVID-19 related effects on air traffic are still on-going, the estimates presented also depend on the evolution of the current situation.

Overall, based on the goals assumed here, we find that both aviation fuel burn and NO_x emissions will continue to increase in the coming decades, unless actions beyond these targets are taken. More frequent aircraft replacement and more optimistic operational improvements do not substantially alter this result. However, in this work, we do not account for innovations in the energy source, fuel used, or non-conventional designs that could be introduced. Specifically, in the operations modeled in this work, we assume the use of conventional jet fuel and thus we do not explicitly take into account the take-up of sustainable aviation fuels (SAF). However, we note that drop-in SAFs do not substantially impact the fuel consumption, and studies show that their NO_x emissions also do not substantially differ from conventional jet fuel [36]. Finally, we note that we do not capture new technologies that deviate substantially from the current configurations, such as electric, hybrid or hydrogen-fueled aircraft. This work further highlights the need for such technologies or other demand-based interventions in order to meet aviation's environmental goals. Future work could introduce these new technologies to the modeling chain described here.

VI. Appendix

Table 4 Annual specific fuel consumption reductions applied. Configurations in italics are used in the baseline forecast.

	k_{op}		k_{tec}			
	Baseline	Low	Low	*Moderate*	Advanced	Optimistic
2018 – 2020	0.330%	0.227%	0.57%	0.96%	1.16%	1.50%
2020 – 2030	0.368%	0.233%	0.57%	0.96%	1.16%	1.50%
2030 – 2040	0.244%	0.132%	0.57%	0.96%	1.16%	1.50%
2040 – 2050	0.000%	0.000%	0.57%	0.96%	1.16%	1.50%

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