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Aircraft Fuel Efficiency Improvements: The Pathway to Evidence-Based Forecasts

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Abstract
Aircraft fuel efficiency has improved significantly since the introduction of the first commercial jets in the 1950s. Many scenarios for decarbonizing air travel rely, in part, on the unabated continuation of this trend. However, with many aircraft sub-efficiencies approaching physical or economic limits, a scenario of diminishing returns is more likely. To overcome this limitation in present studies, we must improve the quality of future aircraft efficiency forecasts. As a first step, we analyze historical efficiency drivers and dis-aggregate overall efficiency improvements. We then determine sub-efficiency limits using public domain sources. Finally, we assess advancements in future aircraft technologies and design concepts.

1. Introduction

Aviation is presently responsible for 2.4% of global carbon emissions [1]. The effective radiative forcing associated with additional non-carbon forcing terms from aviation emissions is an area of active research [2]–[4]. Best estimates currently indicate that *"aviation emissions are currently warming the climate at approximately three times the rate of that associated with aviation CO2 emissions alone"* [2]. At the same time, industry assumes a compound annual growth rate in excess of 3% from the present day to 2050, resulting in 10 billion passengers being carried 22 trillion kilometres by air in 2050 [5]. This trend is driven primarily by the reciprocal relationship between air transport and economic growth [6], illustrated in Fig. 1. This would result in increased anthropogenic pressure on the natural ecosystem, leading to a progressive deterioration in the planetary boundary indicators [7]. A growing number of governments have therefore agreed to decarbonize economic activity, including the transport sector.

2. Sustainability Policy and Efficiency

The European Union in 2019 adopted legislation now referred to as *the Green Deal*, effectively committing to climate neutrality by 2050 [8]. In the United States, a similar target has been set by the executive branch in 2021 through *Executive Order 14057* [9]. In order to meet these targets, specific measures will be taken in the context of aviation. Generally, emissions reductions can be achieved by reducing the number of flights, increasing fuel efficiency or by developing low-carbon fuels [5].

In addition to economic measures and research on the production of low-carbon fuels, efforts on further improving the fuel efficiency of aircraft are ongoing, albeit at diminishing returns. Improvements slowed slightly over the past two decades, from 2.4% per year for 2000-2010 to 1.9% for 2010-2019 [10]. This is a testament to the large gains in efficiency already achieved since the introduction of the first commercial jet aircraft in the 1950s. At the international level, the International Civil Aviation Organization (ICAO) in 2017 introduced carbon emissions regulation in Volume III of Annex 16 to the Chicago Convention [11]. This is in addition to its long-term aspirational goal of 2%/year annually until 2050, at the fleet level. The ICAO assembly, however, recognized that *"the goals (...) would not attribute specific obligations to individual States, and the different circumstances, respective capabilities and contribution of*

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developing and developed States to the concentration of aviation GHG emissions in the atmosphere will determine how each State may voluntarily contribute to achieving the global aspirational goals." [12, §4-5].

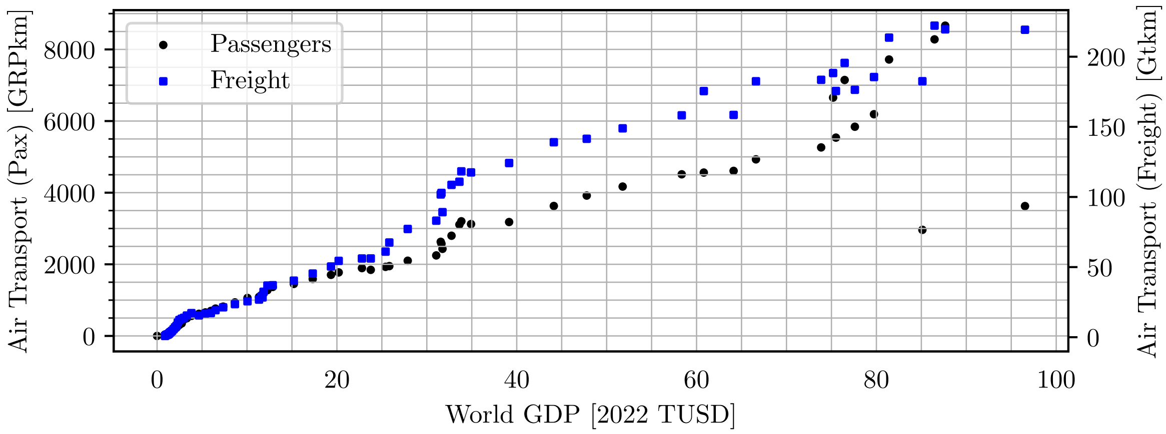

Figure 1: Annual world gross domestic product (GDP) in 2022 U.S. Dollars compared to corresponding air transport volumes for passengers and freight, for the years 1950-2022. Air transport has historically been tightly linked to economic growth. Note the drop in passenger traffic in 2020 and 2021 due to the travel restrictions imposed during the COVID-19 pandemic. Air freight, which played a significant role in the distribution of medical equipment and the COVID vaccines, was not affected to the same degree. Source: GDP data (1950-1960) from the New Maddison Project Database [13], GDP data (from 1960) from the World Bank [14], passenger data from Airlines for America via ICAO via Our World in Data [15], freight data (1950-1960) from Fig. 11.3 in [16], freight data (from 1960) from ICAO via the World Bank [17]. Abbreviations: Pax - passengers, GDP - gross domestic product. Units: GRPkm - giga revenue-passenger-kilometers, Gtkm - giga metric-tonne-kilometers, 2022 TUSD - tera (trillion) U.S. Dollars (2022 value).

3. Future Aircraft Fuel Efficiency

Historically, fuel efficiency improvements have been driven primarily by economic considerations [18]. Socially driven public policy on the other hand has played a larger role in the reduction of aircraft noise [18]. Various high-level publications have investigated the underlying historical drivers of efficiency improvement in different aircraft systems, including propulsion systems [19][20] and overall efficiency [21][18].

However, a preliminary literature review has found that past and future efficiency improvements are often discussed only superficially in government and industry reports, and many life-cycle assessment studies of future air transport (for instance, *"Future efficiency improvements are expected to continue at a much lower rate."* [22]). With respect to historical efficiency data, this is done without reference to the underlying drivers of overall improvements or their physical limits. With respect to projections, this is done without reference to the underlying assumptions on incremental technological improvements or the introduction of novel aircraft designs.

Since overall efficiency is an aggregate metric, it is affected cumulatively by a set of variables or sub-efficiencies, such as propulsive efficiency, weight, or the seat load factor. However, a dis-aggregation showing the contribution of the underlying drivers of efficiency improvements, including advances in metallurgy and composite materials, on overall efficiency has not been performed to date.

For future efficiency, most recent estimates in academic literature range from 1.3%/year (2019-2050) [23] to 2.1%/year (2020-2050) [24], in line with the more conservative scenarios provided by different international organizations listed in Table 1. Unfortunately, we find that even publicly funded research projects use proprietary efficiency models in their publications (for instance, Grewe et al. [25]).

The associated lack of transparency makes it difficult to assess the validity of the models, reproduce them or build on existing work. We therefore aim to create transparent, public-domain, evidence-based scenarios of future aircraft fuel efficiency. This will include upper bounds parametrized by physical and economic limitations. We expect this data

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Table 1: Selection of the most recent scenarios for future passenger aircraft efficiency provided by various international organizations and industry groups. For context, the ICAO long-term aspirational goal (LTAG) was set at 2% for the period 2020-2050 [26].

Organization	*Timeframe*	*Forecast*	*Source*
ICCT	2019-2034	1.08%/yr	2022 [27, Table 2]
ICCT	2035-2050	1.15-2.16%/yr	2022 [27, Table 2]
ICCT	2020-2034	up to 2.2%/yr	2020 [28, Sec. 4]
IATA	~2025-2035	<1%/yr	2019 [29, Exec. Summ.]
IATA	2035-2050	up to 3%/yr	2019 [29, Exec. Summ.]
ICAO	2022-2050	1.2-1.31%/yr (`IS1` scenario)	2022 [30, Sec. 4]
ICAO	2022-2050	1.35-1.47%/yr (`IS2` scenario)	2022 [30, Sec. 4]
ICAO	2022-2050	1.55-1.67%/yr (`IS3` scenario)	2022 [30, Sec. 4]
WEF (CST)	2020-2050	1%/yr	2020 [31, Fig. 2]

The most detailed public reports on scenarios for future aircraft efficiency include the *Appendix M3 (Technology Sub Group Report)* of the *ICAO LTAG Report* [32] and *CLEEN Project report* [33]. Abbreviations: ICCT - International Council for Clean Transportation, ICAO - International Civil Aviation Organization, IATA - International Air Transport Association, WEF (CST) - World Economic Forum (Clean Skies for Tomorrow initiative).

will be most useful to life-cycle assessment practitioners, who rely on forecasts for future aircraft efficiency in their assessment of the environmental impact of future air transport systems.

4. Methods and Data Collection

Overall aircraft fuel efficiency, or energy usage E_U, can be determined by combining the Breguet Range (Eq. (1)) with the amount of fuel burnt per ASK (Available Seat Kilometer) (Eq. (2)). ASK represents the distance flown by an aircraft multiplied by the number of seats available to passengers.

$$R = \frac{V_0(L/D)}{g \cdot TSFC_{\text{Cruise}}} \cdot \ln\left[1 + \frac{W_{\text{fuel}}}{W_{\text{payload}} + W_{\text{structure}} + W_{\text{reserve}}}\right] \tag{1}$$

$$E_U = \frac{LHV \cdot W_{\text{fuel}}}{\text{Seats} \cdot R} \tag{2}$$

R : Range [km]
(L/D) : Lift-to-Drag Ratio
$TSFC_{\text{Cruise}}$: Thrust Specific Fuel Consumption during cruise [g/kNs]
W_{payload} : Payload Weight [kg]
W_{reserve} : Reserve Weight [kg]
E_U : Energy Usage [MJ/ASK]
V_0 : Velocity [km/s]
$g = 9.81$: Gravitational Acceleration [N/kg]
W_{fuel} : Fuel Weight [kg]
$W_{\text{structure}}$: Structural Weight [kg]
LHV : Lower Heating Value [MJ/kg]
Seats : Available Seats

4.1 Aircraft Sub-Efficiencies

Overall aircraft fuel efficiency is an aggregate metric, determined by a number of aircraft parameters, including weight and drag. To better understand the contribution of different aircraft sub-systems to overall efficiency, we use a set of sub-efficiencies. Following Lee et al. [34] and Babikian et al. [35], we use propulsive, structural, aerodynamic and operational efficiencies.

Each sub-efficiency is in turn limited either by physical or economic considerations. Improvements can come from both operational or technological changes: at the level of routing, improved airspace management can reduce holding times or provide access to more direct airways. At the level of aircraft design, improvements in material science can reduce air resistance and overall fuselage weight. At the level of engine design, high-performance ceramics and alloys and resulting higher bypass ratios can reduce specific fuel burn.

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Therefore, any reasonable projection of overall efficiency must consider the underlying sub-efficiencies, their physical limits, their respective historical rates of progress, the economic implications of further improvements and the technological readiness level of solutions affecting the sub-efficiency.

To collect historical data on sub-efficiencies at the aircraft level, the possibility to use existing aircraft performance analysis tools and databases was examined. Unfortunately, the license agreement of the comprehensive Eurocontrol BADA (Base of Aircraft Data) database prohibits the comparison of different types of aircraft, as data is provided by, and remains courtesy of, various aircraft manufacturers [36]. Therefore, available open-source aircraft data was used to calculate and estimate the trajectories for individual efficiency improvements. Fig. 2 shows an overview of the individual sources used.

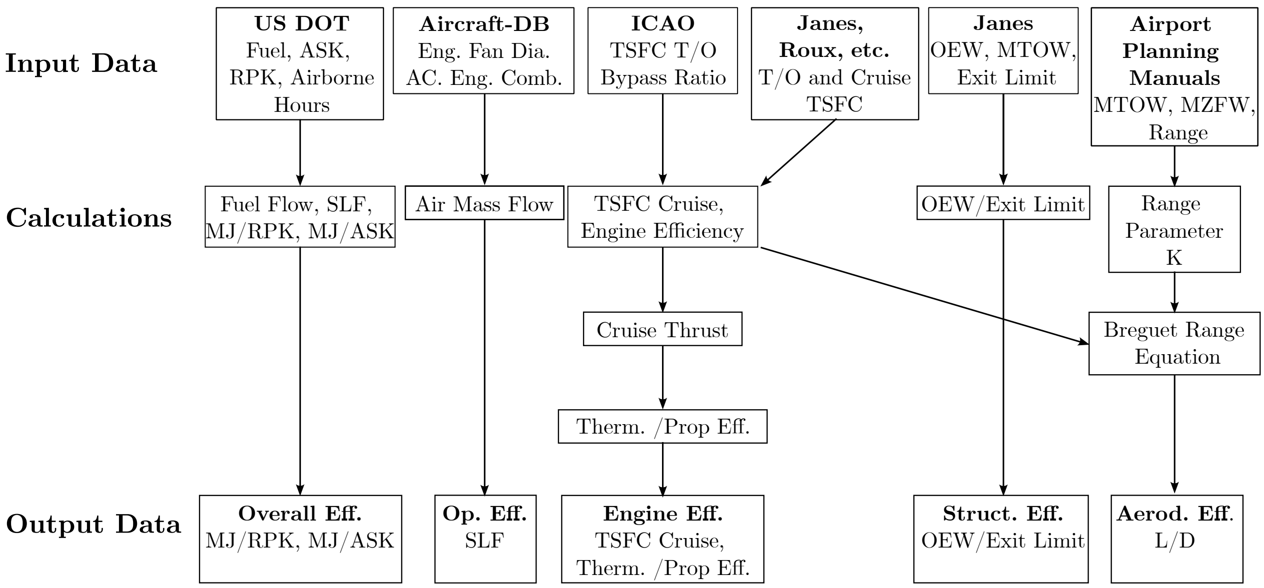

Figure 2: Creation of a Database to assess overall, operational, engine, structural, and aerodynamic efficiency. Sources: US DOT (US Department of Transportations [37], Aircraft-DB (Aircraft Database) [38], ICAO (ICAO Emissions Databank) [39], Janes (Janes all the World's Aircraft) [40], Roux (Turbofan and Turbojet Engines: Database Handbook) [41], Civil Jet Aircraft Design [42], Jet Engine Specification Database [43], Turbofan Engine Database as a preliminary Design Tool [44], Airport Planning Manuals [45] [46]. Abbreviations: MJ - Mega Joules, RPK - Revenue Passenger Kilometers, ASK - Available Seat Kilometers, SLF - Seat Load Factor, TSFC - Thrust Specific Fuel Consumption, T/O - Take-Off, OEW - Operating Empty Weight, MTOW - Maximum Takeoff Fuel Weight, MZFW - Maximum Zero Fuel Weight, L/D - Glide Ratio.

A Python-based modeling pipeline was utilized to perform the calculations, resulting in a table of 41 aircraft, which were released during the period from 1959 until 2019, for which each individual sub-efficiency is known. The individual sub-efficiencies were then normalized with respect to the first aircraft, which was introduced in our data set, the Boeing B707-100. New aircraft are not released annually and have additionally different trade-off characteristics between sub-efficiencies. This makes it hard to compare certain aircraft with each other, therefore the efficiency improvements were normalized. For these normalized efficiency improvements, a fourth-order polynomial fit was performed to capture the efficiency trend. The fit was chosen based on the increase in R^2 in comparison to lower-order polynomials.

4.2 Aircraft Efficiency Decomposition

An index decomposition analysis (IDA) was conducted to evaluate the contribution of each sub-efficiency to the overall efficiency. The IDA method was chosen because it is suitable for top-down approaches, even when there is limited data available [47]. To perform the decomposition, the Log Mean Divisia Index (LMDI) method was employed. The LMDI method is recommended for situations where efficiency improvements follow a multiplicative pattern, as is the case for aircraft sub-efficiencies [48]. By utilizing the LMDI method, it is possible to express these improvements in an additive

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manner, allowing for a clearer understanding of the contributions made by each sub-efficiency.

The decomposition analysis aims to isolate the effects of individual factors. To achieve this, the change in overall efficiency between the initial year (0) and the target year (t) is calculated as $C_t - C_0$. To calculate the contribution to the overall efficiency for each sub-efficiency, the change in a certain sub-efficiency is multiplied by the logarithmic mean function $L(C_t, C_0)$ for the overall efficiency. For instance, ΔC_{Eng} represents the contribution of engine efficiency improvements to the overall efficiency improvements. The final decomposition function, as described in Eq. (3), calculates the residual term ΔC_{Rsd}, which represents the part of the overall efficiency changes, that cannot be attributed to a specific sub-efficiency [49] [50].

$$\Delta C_{\text{Tot}} = \Delta C_{\text{Eng}} + \Delta C_{\text{Str}} + \Delta C_{\text{Aero}} + \Delta C_{\text{Ops}} + \Delta C_{\text{Rsd}} \tag{3}$$

where:

- $\Delta C_{\text{Tot}} = C_t - C_0$ – Overall Efficiency
- $\Delta C_{\text{Eng}} = L(C_t, C_0) \ln\left(\frac{E_t}{E_0}\right)$ – Engine Efficiency
- $\Delta C_{\text{Str}} = L(C_t, C_0) \ln\left(\frac{S_t}{S_0}\right)$ – Structural Efficiency
- $\Delta C_{\text{Aero}} = L(C_t, C_0) \ln\left(\frac{A_t}{A_0}\right)$ – Aerodynamic Efficiency
- $\Delta C_{\text{Ops}} = L(C_t, C_0) \ln\left(\frac{O_t}{O_0}\right)$ – Operational Efficiency
- ΔC_{Rsd} – Residual term.

5. Preliminary Results

Results from the IDA are shown in Fig. 3. We find that from 1960 until 2020, overall aircraft efficiency has improved by 400%. Half of the improvement can be attributed to improvements in engine efficiency. The rest is equally split between structural, aerodynamic and operational efficiency. Interestingly, most direct improvements in structural efficiency can be dated back to the 1960s, indicating that subsequent weight savings were offset by aircraft performance or traded for improvement in other sub-efficiencies. Regarding aerodynamic efficiency, Fig. 3 shows a small efficiency decrease during the 1960s and 1970s. This corresponds to the introduction of larger turbofan engines with higher BPR (Bypass Ratio), starting with the JT9D series in 1970. The larger turbine diameter resulted in higher drag and an associated decrease in aerodynamic efficiency. The seat load factor (SLF), used as a proxy for operational efficiency, has also slightly decreased in the time period from 1960 until 1978. In 1978, the U.S. airline deregulation act was introduced [51]. Thereafter, constant improvements in SLF can be observed until the most recent drop during the COVID-19 pandemic.

The residual term in the decomposition accounts for efficiency improvements that cannot be attributed to any one individual sub-efficiency. Overall, this term is rather low, indicating that the efficiency improvements can be assigned reliably to the different sub-efficiencies.

Regarding future improvements, we expect little progress in lift-induced drag on conventional tube-and-wing designs, since manufacturers are expected to stay inside a certain FAA (Federal Aviation Administration) box category and AR (Aspect Ratio) has not evolved since the 90s. Even the 777X, equipped with a large wingspan and foldable wings, will not break this trend featuring an AR of "only" 9.96 [52].

6. Future Work

Ongoing efforts are focused on calculating technical, economic and operational limitations for each sub-efficiency. For engine efficiency, these are the technical limitations of propulsive and thermal efficiencies with respect to BPR, OPR (Operating Pressure Ratio) and TET (Turbine Exit Temperature) [19]. For aerodynamic efficiency, these include technical limitations regarding parasitic and lift-induced drag with respect to the skin friction and aspect ratio. Operational limitations regarding the wingspan to comply with current regulations will be included as well. For structural efficiency, the estimation of future weight savings from advanced materials remains a significant challenge. Preliminary findings

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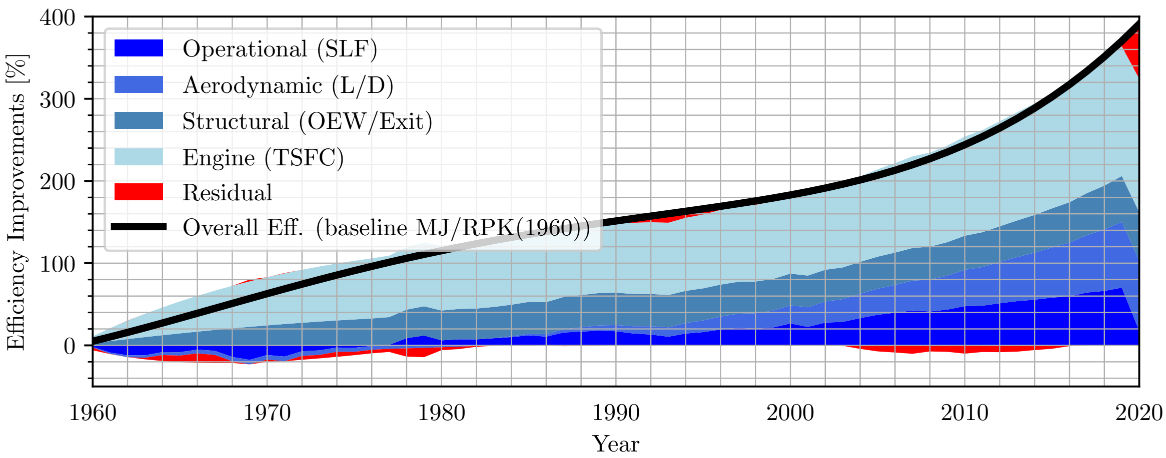

Figure 3: Index Decomposition Analysis for technological and operational (SLF) efficiency gains. The Residual term includes efficiency changes that cannot be attributed to a specific sub-efficiency. Improving overall efficiency leads to a lower MJ/RPK value, which in turn leads to an improvement in the MJ/RPK metric. Abbreviations: SLF - Seat Load Factor, L/D - Lift-to-Drag Ratio, OEW - Operating Empty Weight, Exit - Passenger Exit Limit, TSFC - Thrust Specific Fuel Consumption, MJ - Mega Joules, RPK - Revenue Passenger Kilometers.

suggest that historically, these have often been used offset by improved aircraft performance [53]. Further expert interviews will be conducted. The public-domain-derived aircraft efficiency dataset will thereafter be cross-validated with partners from the industry.

Following the elaboration of technological limitations, scenarios for future aircraft technologies and design concepts will be incorporated into the analysis. Ultimately, bounded learning curves will be calculated to describe scenarios for future efficiency improvements at the fleet level. These transparent scenarios will then be compared with existing work listed in Table 1.

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