Technology Assessment of Future Air Transport Systems

Improving Emissions Forecasts with Physical Limits and Decomposition Analysis

Conference Poster

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Technology Assessment of Future Air Transport Systems

Improving Emissions Forecasts with Physical Limits and Decomposition Analysis

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INTRODUCTION

Air transport presently constitutes around 2% of global carbon emissions [1]. Industry and policy makers have therefore agreed to work towards "net-zero air transport by 2050" [2]. One scenario is shown in Figure 1 below. In principle, three major pathways allow for a reduction of air transport carbon emissions:

1. Reducing the number of flown passenger/freight-kilometres ("market measures")
2. Decarbonization the primary energy carrier ("SAF")
3. Increasing overall aircraft efficiency ("technology")

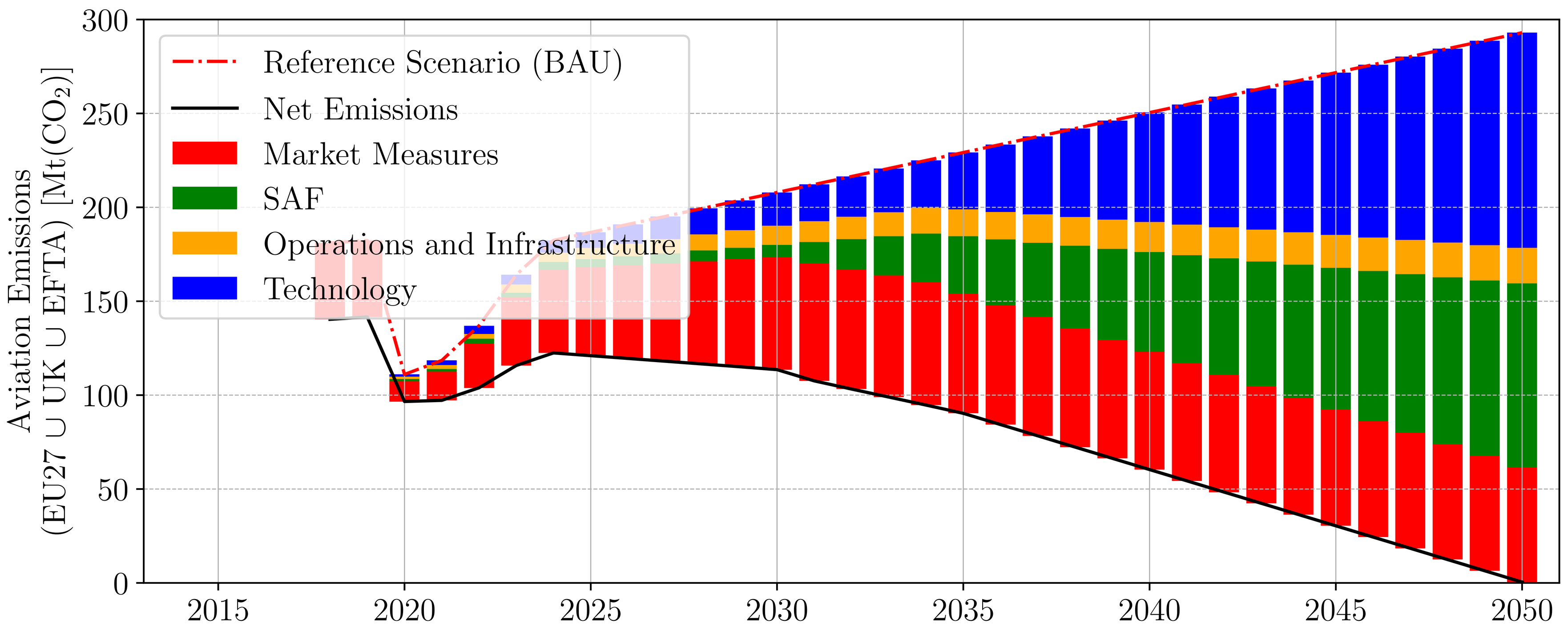

Figure 1: European Environmental Agency scenario for reducing aviation-related carbon emissions to zero by 2050. Note the significant role that technological improvements ("increased efficiency") are playing from the year 2035. Abbreviations: SAF – sustainable aviation fuel, BAU – business as usual. Source: Adapted from European Aviation Environmental Report (2022)

Research and development efforts related to the production of non-fossil fuels and further increases in aircraft efficiency have therefore been increased over the past decade. However, high levels of historical efficiency improvements have already been achieved in air transport. For instance, contemporary passenger aircraft burn 95% less fuel per passenger-kilometre than the first jet aircraft of the 1950s [3]. Sustaining this historical rate of efficiency improvements, while at the same time introducing new aircraft types that allow for the use of non-fossil fuels will require revolutionary, rather than evolutionary technology.

THE ROLE OF TECHNOLOGY ASSESSMENT

Several radically different aircraft designs are competing in the race to develop the next generation of commercial passenger aircraft. This includes the design of the aircraft fuselage as well as the associated propulsive system. Anything from a flying-wing design powered by hydrogen fuel-cells to the conventional "tube-and-wing" design powered by a row of small battery-driven fans has been proposed by industry. To determine which future aircraft design will ultimately result in the lowest carbon emissions per passenger kilometre, these different designs must be assessed based on their prospective performance. While many scientific publications simply "extrapolate" historical rates of efficiency improvement into the future, this approach is unlikely to yield realistic projections. This is because many sub-systems of the aircraft are approaching the physical (thermodynamic, aerodynamic) limits. Only by understanding the historical progress in efficiency at the sub-system level, and by providing associated physical limits, can we make reasonable predictions about the performance of future aircraft.

METRICS: AIRCRAFT SUB-EFFICIENCIES

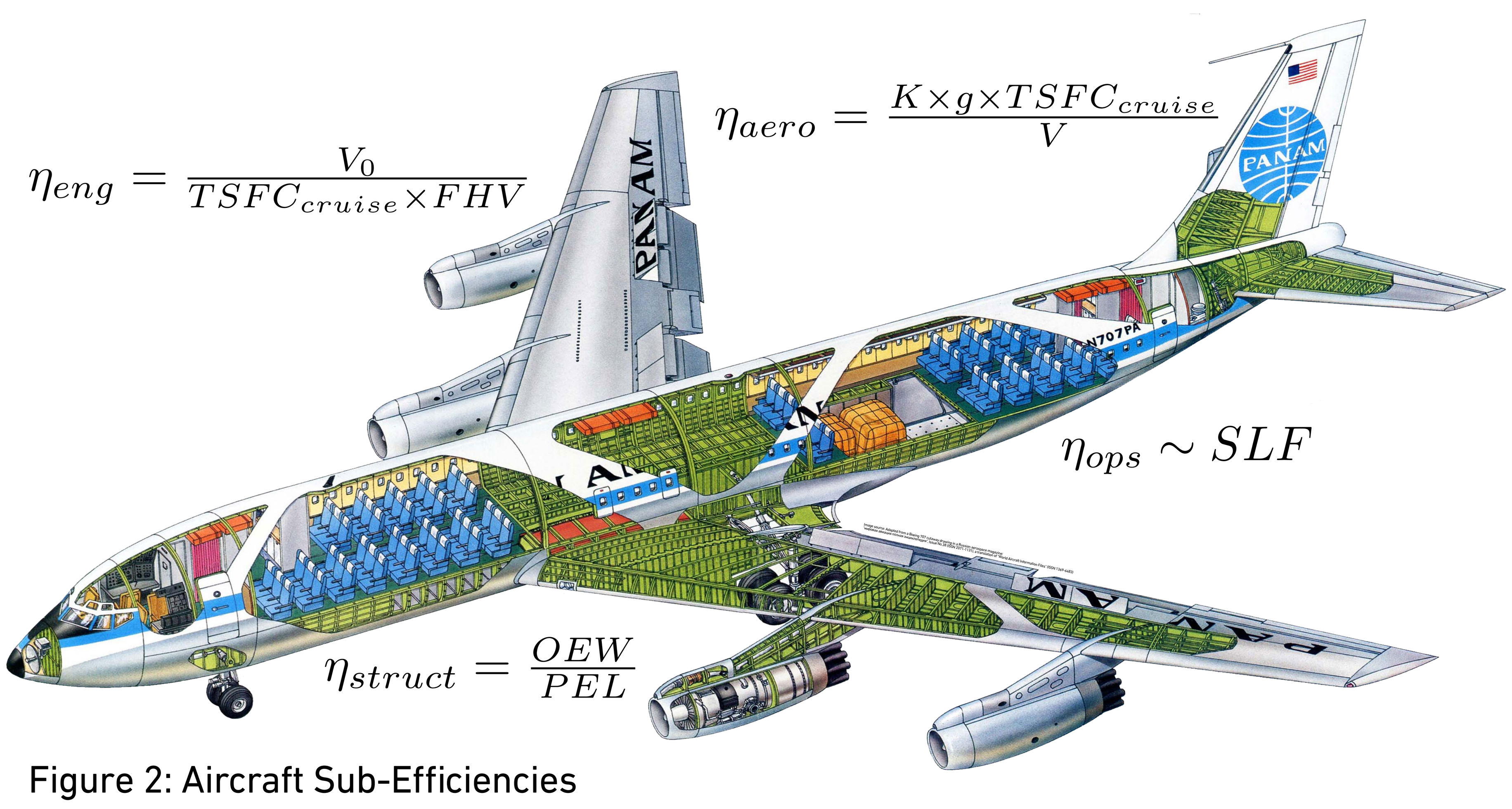

Figure 2: Aircraft Sub-Efficiencies

Overall aircraft fuel efficiency (η) is an aggregate metric, determined by several 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. [4] and Babikian et al. [5], we used engine (η_{eng}), structural (η_{struct}), aerodynamic (η_{aero}) and operational (η_{ops})efficiencies, shown in Figure 2. Each sub-efficiency is in turn limited either by physical or economic considerations.

Data on each sub-efficiency was gathered either directly or was calculated from public domain data. This presented a significant challenge since most aircraft performance data, even for historical aircraft, remains proprietary. Therefore, proxy metric were identified, all of which were part of mandatory reporting standards. For instance, the engine efficiency, shown in Figure 3 below, was computed from emissions data reported to the EASA (European Union Aviation Safety Agency). Physical limits were then determined from the governing equations of thermodynamics (Brayton-cycle for a turbofan engine).

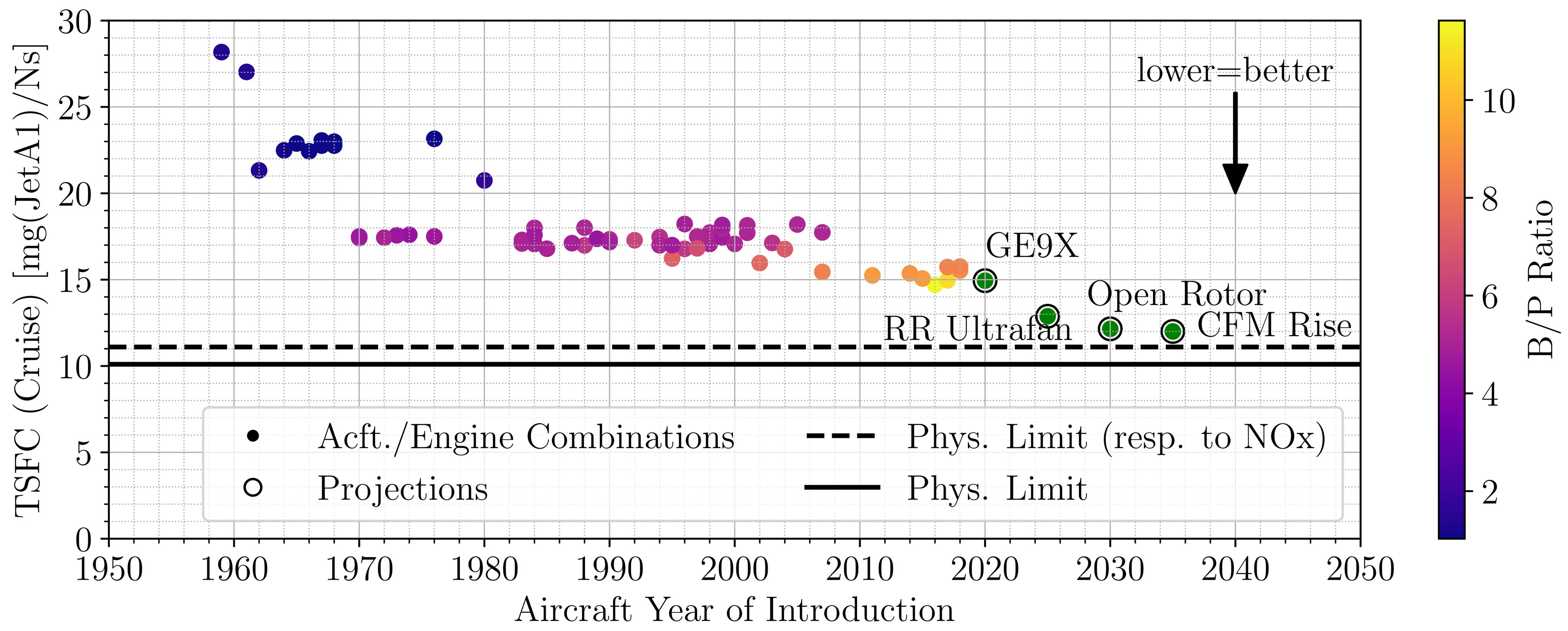

Figure 3: Historical improvements and future projections in overall engine-efficiency of commercial aircraft since 1955. The physical limit, based on thermodynamic calculations, is shown as "theoretical limit". A more realistic limit that considers trade-offs between engine efficiency and NOx emissions is shown as "practical limit with respect to NOx". The diminishing returns of ever more complex turbofans becomes evident in the flattening of the efficiency curve. Revolutionary, rather than evolutionary technology improvements will therefore be required to sustain the historical rate of efficiency improvement.

METHODS: INDEX DECOMPOSITION ANALYSIS

To assess the contribution of each sub-efficiency to the overall efficiency, Index Decomposition Analysis (IDA) was used [6]. For instance, to determine the share of overall efficiency improvement attributed to improvements in the engine efficiency between time 1 and time 2, we calculated:

$$\Delta\eta_{eng}(t_1, t_2) = \frac{\eta(t_2) - \eta(t_1)}{\ln(\eta(t_2)) - \ln(\eta(t_1))} \times \left(\frac{\eta_{eng}(t_2)}{\eta_{eng}(t_2)}\right)$$

Performing similar calculations for the other sub-efficiencies and three different years, we were to decompose the efficiency improvements in commercial aircraft from the first jets to present day carbon-fiber-based designs, as shown in Figure 4.

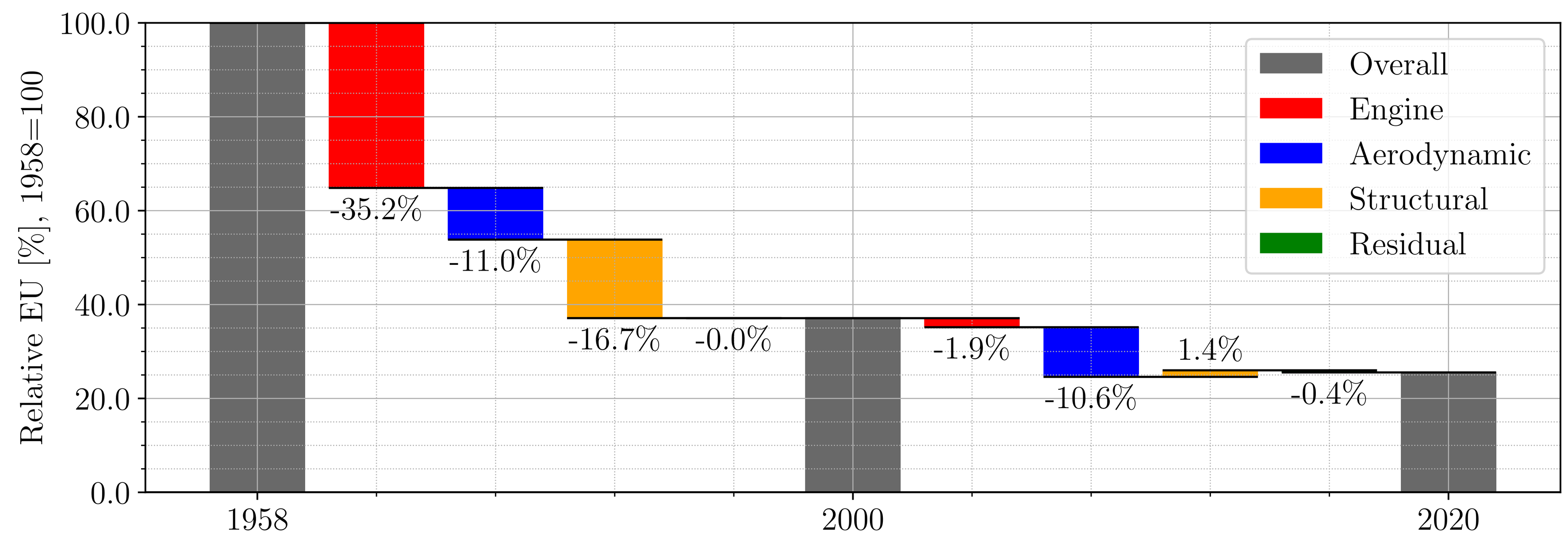

Figure 4: Historical improvements of aircraft efficiency and contribution of individual technological sub-efficiencies between 1960 and 2020. The residual term represents the portion of overall efficiency changes that cannot be attributed to a specific sub-efficiency. Operational efficiency improvements are omitted in this figure. Note the diminishing share of engine improvements, in line with our findings from Figure 3.

CONCLUSIONS AND OUTLOOK

We were, for the first time, able to show the contribution of different aircraft sub-systems on overall efficiency. In addition, we were able to provide physical limits for the associated sub-efficiencies. This constitutes a major step towards better understanding the remaining potential for efficiency improvement in air transport. In future work, we will expand our method to novel aircraft designs, thereby enabling us to make recommendations on which designs will offer the largest environmental benefits.

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