Estimating the Fuel Saving Potential of Commercial Aircraft in Future Fleet-Development Scenarios

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In the face of global climate change and steadily increasing energy prices, various private and public stakeholders of the commercial aviation industry have proclaimed ambitious goals aimed at reducing the global fuel consumption and thus mitigating the future environmental impact of aviation. From today's viewpoint, these goals can only be reached if substantial technological progress is achieved in the various fields of air transportation. Here, the progress in aircraft technologies represents one major enabler. Estimating the impact of next-generation aircraft types on the future fuel demand of the global commercial air transport fleet, and analyzing the remaining carbon-emissions reduction gap relative to aviation's climate goals, are the objectives of this paper. To handle the uncertainty about the future technological progress that affects the global fleet performance, multiple technology-improvement scenarios are investigated. A numerical model of the global air transport fleet is employed to quantify the fleet-wide fuel demand and carbon-emissions reduction impact and conduct sensitivity analyses. The results obtained clearly indicate that the climate goals of the mid-term future cannot be reached solely by integrating next-generation aircraft types into the fleet. Further measures such as the use of biofuels will equally be required.

I. Motivation and scope of study

GLOBAL climate change, an increasing environmental awareness in society, and growing (and highly volatile) energy prices have made various institutions of the commercial aviation industry formulate and proclaim visions that set quantitative goals for limiting aircraft exhaust gas emission quantities and the corresponding fuel consumption of the future global air transport fleet. Among those institutions are the International Civil Aviation Organization (ICAO),[1] the International Air Transport Association (IATA),[2] the Air Transport Action Group (ATAG),[3] and the European Union (EU).[4] Regarding those types of goals that address the emission quantities of carbon dioxide (CO_2), three major steps are envisioned: (1) a fleet-wide efficiency improvement of 1.5% per annum from the present until 2020, (2) a cap of CO_2 emissions from 2020 ('carbon-neutral growth'), and (3) a reduction of the overall CO_2 emission quantities of 50% by 2050 relative to 2005. As the engines of an aircraft usually produce CO_2 emissions in direct proportion to the amount of fuel burned during a flight mission,[5] the above-described goals are equally applicable to the future consumption of liquid fuels in commercial aviation.

To reach those goals, four different fields of measures have been identified, (1) the introduction of advanced aviation technologies, (2) the improvement of aircraft operations, (3) the optimization of the infrastructure, and (4) the use of biofuels and additional new-generation technologies. Therefore, advanced aircraft concepts and technologies as well as alternative fuels are considered to play a major role in enabling a more sustainable and environmentally friendly air transport system in the future.

This paper attempts to quantify this role by estimating the contribution of the most important representatives of the upcoming aircraft generation to aviation's environmental impact mitigation at a system-wide level while particularly focusing on fuel consumption and hence on the resulting fuel saving potential of the next-generation aircraft types considered. The results obtained are then put into context with the carbon-emissions reduction targets stated above in order to analyze the additional efforts that need to be achieved through alternative fuels and further improvements within the air transport chain, considering a time horizon of 2025.

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In order to capture the fundamental uncertainty about the future of commercial aviation and its surrounding conditions adequately, distinct technology-improvement scenarios are portrayed that stipulate alternative development paths of the global air transport fleet on a mid-term basis and thereby enable sensitivity analyses of the inherent system behavior. These scenarios are based on a future reference development of the global air traffic market. Real-life representatives of the upcoming aircraft generation such as the Airbus A320NEO and Boeing 777X are particularly taken into account here.

II. Air transport fleet modeling

Given the goals of this paper, a simplistic comparison of the performance of current and next-generation aircraft types at a single-mission level is not sufficient. Instead, integration and penetration effects of the next-generation types that enter the global fleet at a certain moment in the future have to be taken into account. That is, once a new type has reached technological maturity for commercial operations with an airline, it will not simply replace all of the corresponding older types at once but gradually replace these aircraft and, in this way, replenish the airline's fleet.

In order to capture the integration and penetration effects of the next-generation aircraft and technologies, the "Fleet System Dynamics Model (FSDM)" has been developed at the Institute of Aircraft Design of TU Munich.[6] The fundamental functioning of this model has been derived from the "macro" or "top-down" approach to fleet planning that is based on a relatively high-level aggregate analysis.[7;8] The FSDM essentially translates air traffic market data provided by the user (e.g., growth rates in different regional markets, payload factors, and aircraft production rates) into quantitative data that addresses the future fleet size, composition, and age distribution. This is achieved through the simulation of the global aircraft commissioning, operations, and retirement procedures for distinct world regions and at a global level as a function of time.

A. FSDM: Overview

The FSDM is divided into two model components: the air transport fleet model and the air transport network model. The former dynamically determines the size and structure of the global fleet of commercial transport aircraft on a year-by-year basis. This implies that the smallest time interval considered by the model is one year. The latter defines the air routes that interconnect local air traffic markets with each other to form and represent the global network of air transport routes on which the air transport fleet operates.

The macro approach to fleet planning underlying the FSDM has two decisive consequences for the basic functioning of the model. (1) For each year of simulation, the model requires a target amount of ASKs and ATKs, or alternatively, a target amount of RPKs and RTKs along with load factor data, in order to determine the "capacity gap," which in turn stipulates the amount of new aircraft units to be added to the fleet. For each year of simulation, the model hence determines the fleet that is required to deliver a certain transport performance predefined by the model user. (2) The user must initialize the model by defining a start year of simulation along with an initial fleet of aircraft (including a definition of the fleet size, composition, and age distribution) as well as the initial transport supply that this fleet must deliver.

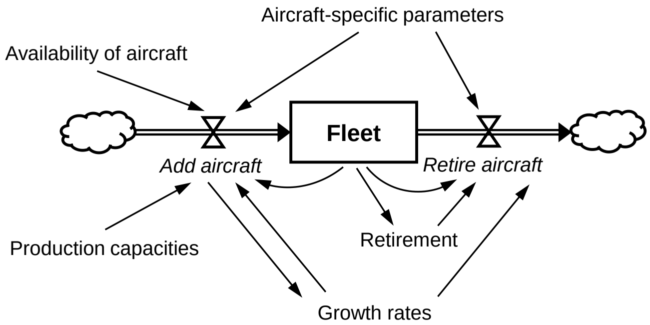

Figure 1. Principal functioning of the FSDM featuring the stock-and-flows principle inherent to the System Dynamics philosophy.

To capture the dynamic evolution of the global air transport fleet, the FSDM uses the principles of System Dynamics.[9] In particular, interdependent stocks and flows are utilized to capture the dynamics of the fleet evolution as a function of time. Fig. 1 schematically illustrates the overall functioning of the model. The fleet (stock) is essentially determined by two flows, the 'Add aircraft'-inflow and the 'Retire aircraft'-outflow. The 'Add aircraft'-inflow is aimed at delivering new aircraft to the fleet, depending on the growth rates of air traffic defined by the user. In addition, it is constrained by both the availability of aircraft (in terms of whether or not a particular type of aircraft is being produced in a specific year of simulation) and the capability of the aircraft manufacturers to deliver the amount of aircraft units required. The 'Retire aircraft'-outflow is determined by an FESG-based aircraft retirement model[10] that is a part of the FSDM. That is, aircraft retirement is accomplished by accessing aircraft-specific survival curves. Given an initial age distribution of the fleet, the model will apply predefined survival curves to the various types of aircraft simulated by the model to determine statistically the amount of aircraft to be retired in each year of simulation.

B. Model assumptions and limitations

Modeling the global air transport system constitutes a challenging endeavor given the high degree of complexity of this system. Therefore, the FSDM relies on some decisive assumptions that were made to simplify the modeling efforts and reduce complexity. On the other hand, these assumptions naturally lead to a degradation of the model accuracy with respect to its capabilities of simulating reality.

1. *Airline competition*

Commercial aviation is an industry sector that is strongly characterized by competition among airlines courting passengers at a local, regional, and global level. However, the modeling of airline competition requires a profound economic understanding that was not available during the work of this paper. As a result, similar to the work of Tetzloff and Crossley,[11] the model simulates "one benevolent, monopolistic airline" that exists to meet all transport demand worldwide.

2. *Fleet allocation*

Usually, airlines will assign their fleets to a route network in a way to maximize profit. Profit maximization is then used as the objective function required for solving the "Fleet Assignment Problem (FAP)."[12] Capturing this real-life behavior in a model, however, would require an in-depth understanding of the various airline business models as well as an incorporation of airline cost functions. Distinct airline business models are not considered in the FSDM, though. Models and functions of airline operating costs are not captured either.

Instead of using profit maximization functions, fuel burn is employed to formulate the objective function for the FAP within the FSDM. That is, the FSDM assigns aircraft to the route network in way to minimize the total fuel consumption of the global fleet in each year of simulation. Although this approach does not exactly reproduce reality, it features two important advantages. (1) The implementation of airline business models and operating cost functions is not necessary, which results in a lower model complexity and lower requirements concerning input data. (2) The effect of a new aircraft on the overall performance of the global fleet in terms of fuel consumption can be examined more precisely, as the model will generate and simulate a fuel-optimal fleet with and without the new aircraft to be assessed. That is, secondary factors that affect the fuel demand of the fleet in reality (due to the profit-maximizing objective function) have no influence on how new aircraft are integrated into the fleet. In this sense, the FSDM defines technological best-case scenarios in terms of global fuel demand.

3. *Simulation periods*

Essential input data addressing the transport supply and the fleet size and composition are required for the FSDM to be initialized. The databases used in the work of this paper date from 2008. Therefore, any simulation performed by the FSDM starts in 2008. Regarding the simulation of future years (i.e., after 2015), the FSDM is capable of simulating periods until 2050 and beyond (provided adequate user input data is available, see section C).

4. *Representation of the global air transport fleet*

Almost 200 different types of aircraft were part of the global air transport fleet that contributed to the total transport supply in 2008.[13] Including all would lead to a very high degree of complexity of the FSDM. Therefore, to keep complexity within manageable limits, the model defines nine distinct aircraft categories to represent the global fleet in 2008 (Table 1). In many other studies, the seat capacity specific to each aircraft type is used to group aircraft.[14;15] However, while this approach may very well lead to an adequate representation of the world fleet with regard to available transport supply, it is unable to represent the fleet in terms of operational and technical characteristics and performance values. The technical representation of the global fleet is vital for the technology assessment objectives pursued by this paper, though. Therefore, aircraft categorization is accomplished here based on multiple aircraft type-specific criteria, including transport performance-related,

Table 1. Initial-fleet aircraft clusters.

Cluster ID	Cluster name	Representative aircraft type	Approx. ASK/ATK-share within cluster (in 2008)
1	Long-range combi	Boeing MD11	43%
2	Long-range heavy	Boeing 747-400	77%
3	Mid-range freighter	Boeing 767-300F	25%
4	Jet commuter	Embraer 190	9%
5	Long-range freighter	Boeing 747-400F	47%
6	Turboprop commuter	ATR 72-500	100%
7	Mid-range	Boeing 767-300	22%
8	Long-range	Boeing 777-200	16%
9	Narrow-body	Airbus A320-200	23%

operational, and technical metrics. A k-medoids algorithm was used for aircraft categorization. ‘Aircraft cluster’ is hence the preferred term employed here to address a specific representative group of aircraft types of the FSDM.

5. *Representation of the global route network*

More than 37,000 different O-D pairs formed the global network of air routes in 2008.[13] Again, representing the entire set of O-D pairs in the FSDM would lead to a significant degree of complexity of the model that would make its handling very difficult. Therefore, the FSDM fundamentally defines six global regions (Africa, Asia, Europe, Latin America, North America, and the Middle East) that together form twenty-one regional and interregional connections referred to as ‘route groups.’ These route groups establish the simulated global air transport network. Distinct stage lengths specific to each aircraft cluster operating on a particular route are employed to characterize each route group. To initialize the FSDM, statistical analyses of the OAG database were conducted to supply a definition of the cluster- and route group-specific stage lengths. During the simulation of the subsequent years, the stage lengths are considered constant over time.

6. *Further model limitations*

In its current version, the FSDM features four additional methodological limitations that decrease the model accuracy. (1) Once defined by the user, the utilization characteristics of each aircraft cluster are treated as constants during the fleet simulation. (2) The FSDM always retires aircraft on a statistical basis, regardless of the current situation of aircraft demand. (3) The FSDM does not support the modeling of temporary aircraft storages that airlines undertake in reality during short periods of economic decline in order to adapt their transport capacities accordingly. (4) Once set by the user, the seat and freight load factors are treated as constants.

On the one hand, integrating the above capabilities into the FSDM would certainly increase the overall model accuracy (and equally raise the model complexity by the same degree). On the other hand, a validation of the current version of the model (not presented in this paper) revealed that even without these capabilities, the FSDM is very well capable of determining a realistic development of the global air transport fleet.

C. User input data required

The FSDM requires a range of input data that have to be supplied by the user in order to enable the proper functioning of the model. The *target year of simulation* stipulates the final year of the fleet simulation. *Current aircraft production intervals* define the time intervals during which the types of the initial fleet are produced. *Next-generation aircraft data* define which types of aircraft will enter the fleet in the future. The user must provide the full range of aircraft data including performance and utilization data, and survival curves. *Next-generation aircraft production intervals* define the time intervals during which the future types are produced. *Production capacities* define the total amount of aircraft that can potentially enter the fleet as well as the maximum amount of aircraft units of a particular next-generation aircraft type available to the fleet in each year of simulation. *Regional market growth factors* define the year-on-year change of the RPKs and RTKs in each one of the 21 route groups between 2008 and the target year of simulation. *Target payload factors* define the seat and freight load factors that the monopolistic airline represented in the FSDM intends to achieve in each one of the 21 regional markets.

D. Aircraft performance modeling

Aircraft performance modeling is an essential capability of the FSDM. The aircraft performance model (APM) employed here is fundamentally based on the Base of Aircraft Data (BADA) that has been created and is now being maintained and distributed by Eurocontrol.[16] Over the last years, BADA has become a widely utilized and recognized APM in the international scientific community. Today, it can certainly be considered as a standard tool for performance simulation purposes of civil aircraft.

The BADA APM has been implemented in the FSDM to primarily determine the fleet-wide fuel consumption and CO_2 emission quantities. The model can also calculate further emission substances like NO_x, CO, and unburned hydrocarbons, provided that adequate data is available (e.g., supplied by the ICAO Aircraft Engine Emissions Databank). The model then determines the quantities of these substances through the “Boeing Fuel Flow Method 2.”[17]

Next-generation aircraft that are not officially captured by the BADA database are simulated by deriving the necessary BADA parameters from existing aircraft types and varying them until the desired mission performance (i.e., fuel burn in particular) is achieved. BADA parameters of entirely new aircraft concepts are generated through a stand-alone conceptual design tool developed at the institute.[18]

III. Reference air-traffic-growth scenario and future fleet inventory

In the literature, research projects and business reports with varying air traffic growth rates can be found. The challenging task here is to find a realistic and solid reference case of the air traffic development. To this end, growth data from eight future forecasts were collected as described in more detail in the following section.

A. Market forecasts considered

In order to derive realistic air traffic growth rates for a future reference scenario, growth data from eight forecasts were collected that were considered relevant for the aviation industry. These reports feature a typical time horizon that comprises the upcoming two decades. Considered were the Airbus Global Market Forecast (2012),[19] the Boeing Current Market Outlook (2012),[20] the ICAO Environmental Report (2010),[21] the Airport Council International Global Traffic Forecast (2013),[22] the ICAO Global Air Transport Outlook (2012),[23] the ICAO Outlook for Air Transport to the Year 2025 (2007),[24] the Rolls Royce Market Outlook (2009),[25] and the Airport Council International Global Traffic Forecast (2009).[26] For each one of the 21 regional markets covered by the FSDM, the median values of the growth rates published in the analyzed forecasts were calculated (Table 2). When considering these values, the future reference scenario is obviously as optimistic as the various forecasts that were consulted, featuring a global air traffic growth of around 5 percent annually from the present until 2025.

Table 2. Mean growth rates in percent per year of the global market forecasts considered in this paper.

Interregional Routes	Mean
North American - Europe	3.39
North America - Latin America	4.68
North America - Asia	4.88
North America - Middle East	6.27
North America - Africa	6.20
Europe - Africa	4.86
Latin America - Europe	5.17
Europe - Asia/Pacific	5.81
Europe - Middle East	5.40
Middle East - Asia/Pacific	6.69
Middle East - Latin America	7.75
Middle East - Africa	6.20
Africa - Latin America	7.75
Africa - Asia/Pacific	7.67
Latin America - Asia	6.00
Regional Routes	
Africa	5.32
Asia/Pacific	6.18
Europe	2.76
Latin America	5.34
Middle East	4.19
North America	2.34

B. Fleet inventory

To estimate the fuel- and emissions-reduction potential of the next-generation aircraft types under different technology-improvement scenarios (i.e., by varying the fuel efficiency improvements associated to each next-generation aircraft type), today's air transport fleet was reduced to nine representative aircraft clusters, in which each one of the clusters is represented by a typical aircraft type (see section II for more details). The assignment was done on an ASK/ATK-share basis for each cluster. The nine clusters comprise two different types of freighters (mid- and long-range freighters), four clusters for different twin-aisle long-range aircraft, and three single-aisle clusters, of which two are powered by a turbofan and one by a turboprop propulsion system (Table 1).

1. Next-generation and re-engining aircraft programs

Published data from aircraft manufacturers and aviation analysts were used to estimate a possible range of fuel efficiency improvement of the next-generation and re-engining aircraft programs in each cluster (see the Appendix for an overview of the consulted sources). Due to uncertainties underlying the aircraft development phase, performance shortfalls of early entry-into-service aircraft, or performance improvement programs for existing programs, the fuel efficiency improvement was determined for a minimum, mean, and maximum technology-improvement scenario on a seat-kilometer basis (Fig. 2).

For cluster C1 ('Long-range combi') with the MD11 being the representative aircraft type, no successor program was assumed. In the long-haul segment, the Boeing 747-400 of the second cluster is replaced by the stretched, re-engined, and re-winged Boeing 747-8 in 2012 with a mean fuel reduction of 16%, followed by a possible re-engined Airbus A380-800NEO with a 12% fuel reduction potential in 2021 compared to the current A380. A freighter derivative of the Boeing 787-8 was assumed as the next-generation C3 aircraft ('mid-range freighter'), where the production of the Boeing 767 family is expected to be closed by 2019. For the long-range freighter cluster C5, equal mean fuel reductions for the Boeing 747-8F as for the passenger version were assumed. In the long-range twin-aisle cluster C8, current aircraft types like the Boeing 777 and the Airbus A340 families are replaced by the Airbus A350XWB at the end of 2014 and later the re-engined Boeing 777X (8X, 9X) in 2020. An average of 18% of the fuel reduction potential was assumed using analyses predicting fuel reduction potentials between 13% and 20% relative to the existing Boeing 777-300ER. In the long-range twin-aisle aircraft cluster C7, the replacement of currently operating Boeing 767-300s by the Boeing 787 family since 2011, and the A330NEO family starting in 2017 will lead to a fuel reduction between 14% and 20% with an assumed mean reduction of 16%. The regional aircraft market is clustered into two segments (C4: 'Jet commuter' and C6: 'Turboprop commuter'). The Embraer E190 being the representative aircraft type in cluster 4 will be replaced by the Bombardier C-Series in 2015 and Embraer's second generation of the

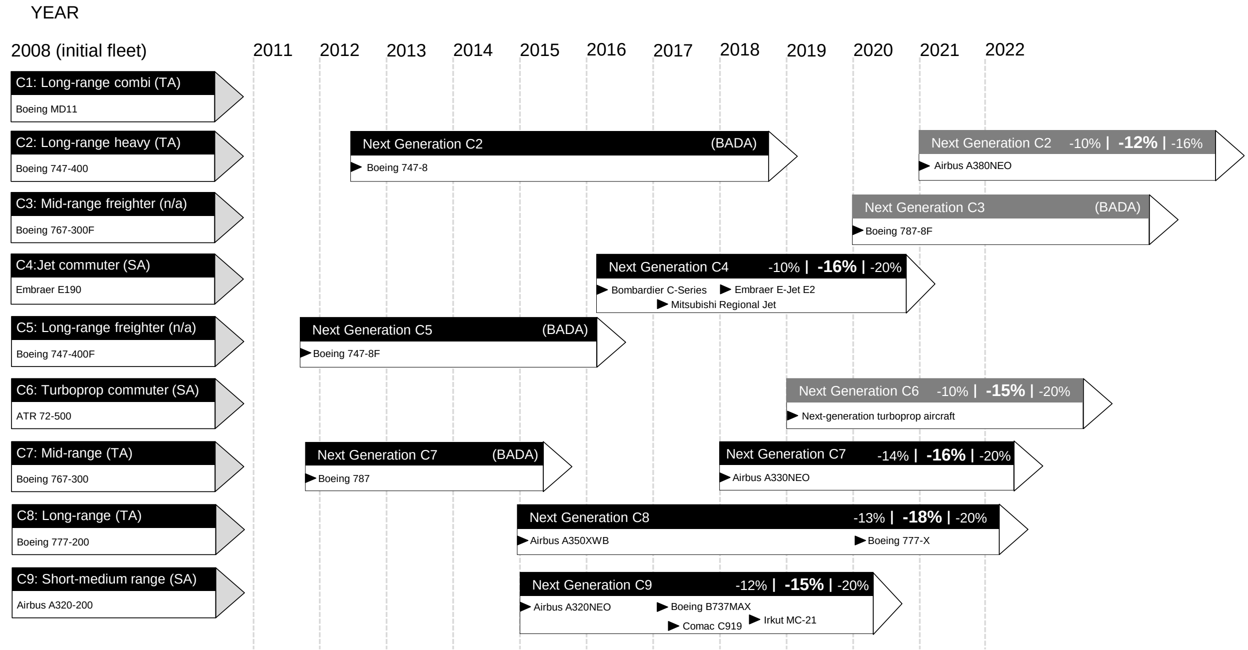

Figure 2. Next-generation aircraft types and associated gains in fuel efficiency. *Grey = values individually assumed by authors.*

E-Jet family in 2018. With these two new families, the fuel-burn reduction of this cluster is expected to be between 10% and 20% with a mean value of 16%. For Cluster 6, next-generation turboprop aircraft programs or significant product enhancements have not been announced for either the Bombardier Q-400 or ATR families so far, but it can be assumed quite certainly that the market will actually demand a further reduction in fuel burn. Therefore, major upgrades, which will potentially reduce fuel burn between 10%, 15%, and 20% were assumed. For the third single-aisle cluster C9, the representative A320 aircraft will be replaced by the A320NEO in 2015, the Boeing 737MAX family in 2017, and the Comac C919 in around 2017. For all aircraft family members (e.g., A319 to A321 and B737-7 to B737-9), fuel-burn reductions of 10%, 15%, and 20% were assumed.

2. Production ramp-ups of the next-generation and re-engining aircraft programs

The production ramp ups for each of the upcoming next generation and re-engining aircraft program out of the nine clusters were summarized into two different delivery schedules: (1) for single-aisle types including clusters C4, C6, and C9, and (2) for twin-aisle types including clusters C2, C7, and C8. For the single-aisle aircraft programs, production ramp-ups for the C-Series, the E2-Jet, the ATR family, and the A320 and 737 families were taken into account. For the twin-aisle production ramp-up, individual ramp-ups for the A380, the 747-8, the 787, the A330, the A350, and the 777 families were taken into account based on statements of aviation experts who were consulted in advance. The results for the single-aisle aircraft (SA) and twin-aisle aircraft (TA) as well as their associated linear regressions are both shown in Fig. 3.

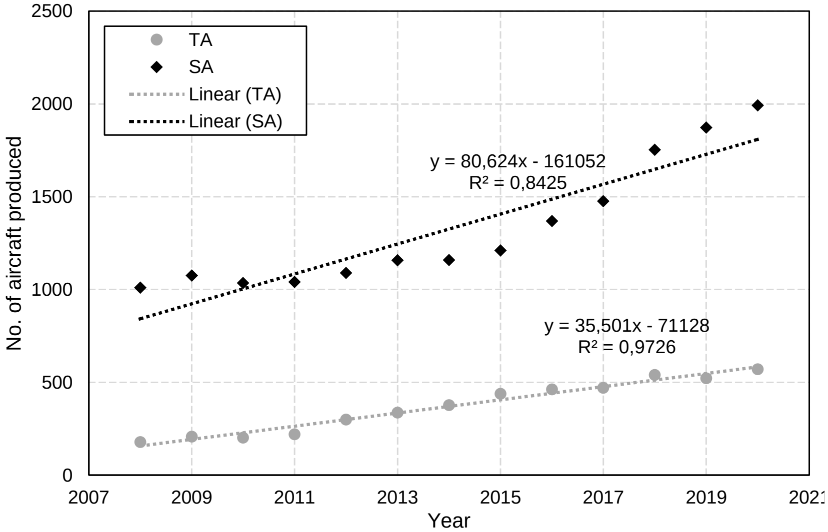

Figure 3. Statistical development of the total annual production rates of all single-aisle (SA) and twin-aisle (TA) aircraft worldwide.

IV. Simulation results

In addition to the input data related to the annual growth rates of future air traffic, three technological advancement scenarios representing the developments with the lowest fuel efficiency improvement rates ('BAD'), the mean rates ('BASIC'), and the highest rates ('BEST') of the next-generation aircraft were defined (see previous section and Fig. 2 for an overview of the next-generation types considered). In order to compare these scenarios with both a zero-improvement scenario and the envisioned climate goals mentioned in the first section of this paper, additional fleet simulations were accomplished with the FSDM.

The zero-improvement scenario was set as an upper-bound scenario at both the fleet and individual aircraft levels. Furthermore, the ATAG targets mentioned in the first section of this paper were included schematically as a lower-bound scenario at the fleet level and the targets of the Strategic Research and Innovation Agenda (SRIA) of the Advisory Council for Aeronautics Research in Europe (ACARE) [27] as a schematic optimum technological path at the aircraft level. (The ATAG targets relevant to this study define (1) an improvement in fleet-wide fuel efficiency of 1.5% annually beginning in 2005 and (2) carbon-neutral growth (concerning net emissions) of the air traffic sector from 2020 onwards.[3])

In Fig. 4, the dotted area illustrates the impact of the technological improvement at the aircraft level on the fleet-wide fuel demand. In this area, all lines of the BAD, BASIC, BEST, and SRIA fleet scenarios can be found. The SRIA fleet scenario simply defines a fuel efficiency improvement of 36% of the representative aircraft of all clusters in 2020 relative to the reference aircraft of the year 2000. The black-striped area represents the gap between the BEST technological improvements and the ATAG targets.

Interestingly, the obtained results show that the fuel efficiency improvements with respect to the SRIA targets lead to a very similar level of the fleet-wide fuel demand relative to the BEST fleet scenario in 2025. Furthermore, the development of the BAD, BASIC, and BEST scenarios do not differ much in terms of the total fuel burn. Moreover, there is a huge gap between each scenario (including the SRIA fleet scenario) and the ATAG targets, indicating that carbon-neutral growth is not feasible solely through technological improvements at the aircraft level.

Fig. 5 suggests an alternative way of examining the fleet-level efficiency improvements by considering the relative fleet emissions performance, which is defined as the emissions-reduction achievement per available seat kilometer

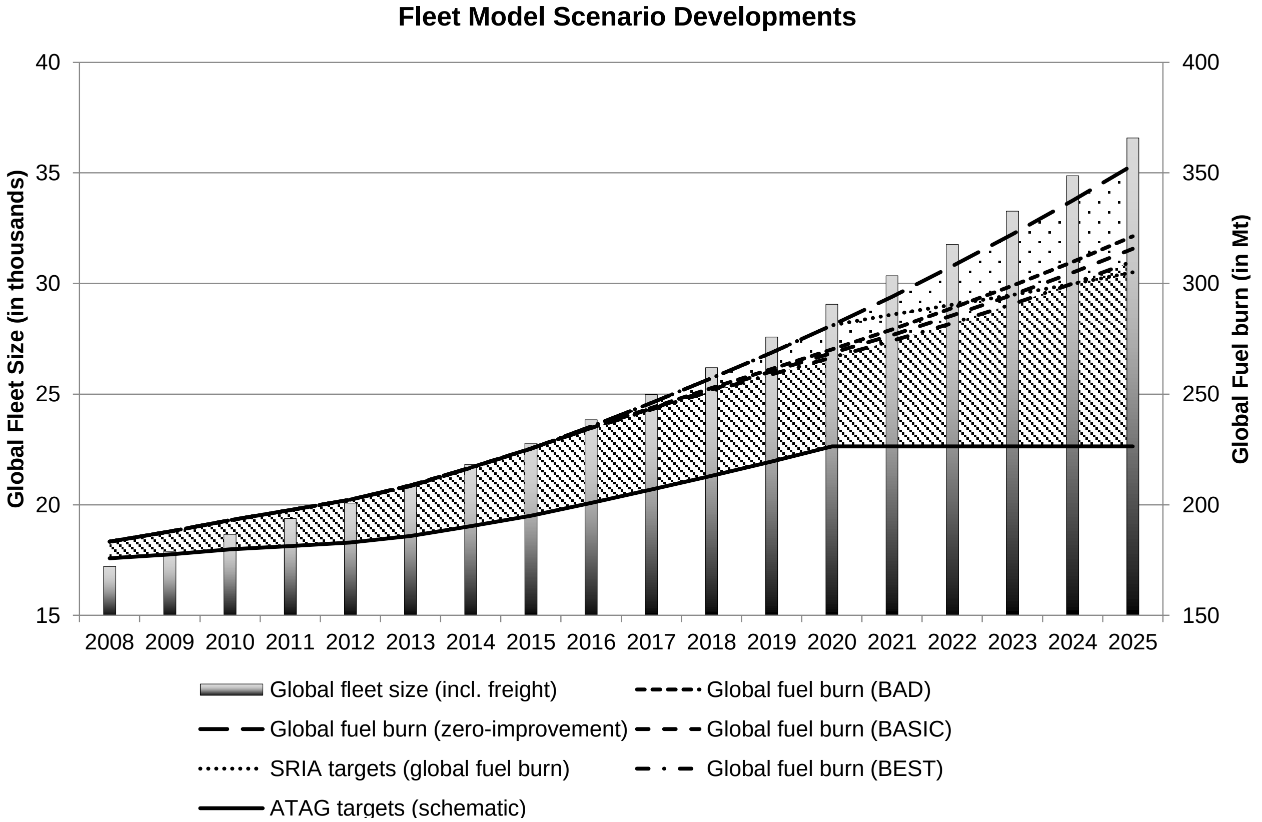

Figure 4. Global fleet-size and fuel-burn development for the BAD, BASIC, and BEST technology-improvement scenarios including the zero-improvement path, and the SRIA and ATAG targets.

(ASK) relative to the transport performance of the entire in-service fleet. This metric can be used for example as a means of comparison towards other modes of transport. Here, technological improvements are expressed in grams of carbon dioxide per ASK (gCO2/ASK). The impact of a next-generation aircraft type as well as the speed of its market penetration is reflected through the slope of each curve. In Fig. 5, the total efficiency improvement becomes very well apparent for each scenario. For example, the BEST fleet scenario reaches a relatively low value of approximately 82 gCO2/ASK that is very similar to the SRIA fleet scenario curve in 2025. However, the BAD-scenario fleet only achieves 85.4 gCO2/ASK in this year. In addition, the zero-improvement scenario also shows a certain degree of efficiency improvement. This is due to the fleet-allocation algorithm of the FSDM that assigns any aircraft to be added to the fleet to those routes of the simulated air transport route network where it achieves its best fuel performance (see section II). As a result, although next-generation aircraft types are not inserted into the fleet in the zero-improvement scenario, the global fleet assignment to the network changes over time towards a more fuel-optimized allocation solution.

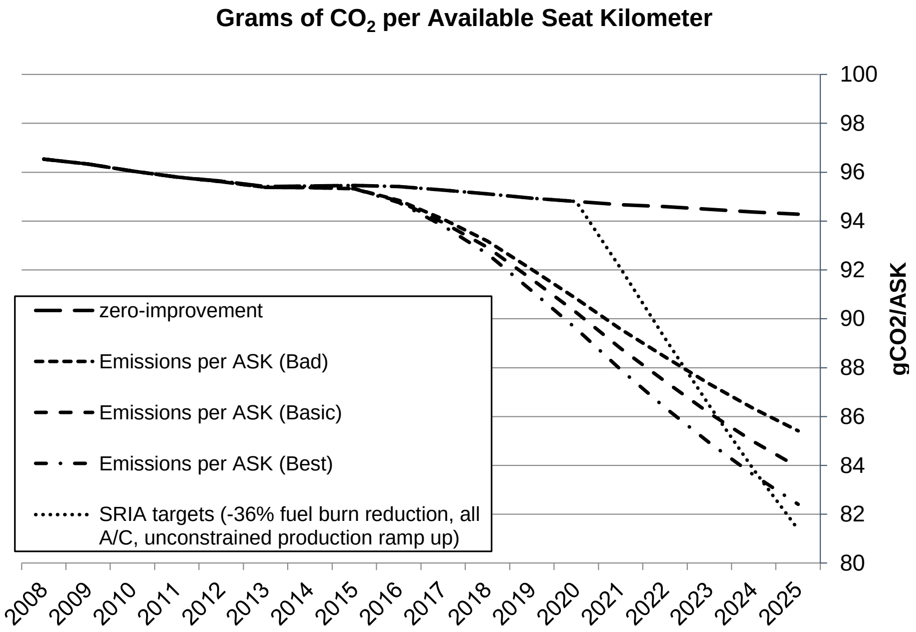

Figure 5. CO_2 emissions developments per ASK for the BAD, BASIC, and BEST technology-improvement scenarios including the 'no fuel efficiency improvement' path, and SRIA targets.

V. Conclusions and future work

The results obtained through application of the FSDM together with the reference scenario of air traffic growth and the three technology-improvement scenarios described above clearly reveal that the ATAG targets cannot be reached solely through an integration of next-generation aircraft types into the global air transport fleet. A significant gap between the fleet-wide fuel and emissions performance on the one hand and the ATAG targets on the other persists even in the BEST fleet scenario that features very optimistic rates of fuel efficiency improvement of the next-generation aircraft under scrutiny (i.e., a fuel efficiency improved by 16-20% relative to the respective predecessor aircraft types).

As a result, other measures must simultaneously be employed to enable a further reduction of the future fuel demand and CO_2 emissions of the global air transport fleet. Not considered during the studies presented in this paper were especially the use of biofuels (that may not reduce fuel consumption but help improve the fleet-wide CO_2 performance when considering their entire well-to-wake life cycle), the optimization of air traffic operations and procedures, and the advancements of the air traffic infrastructure. The future work at the institute will therefore be directed towards an investigation and assessment of the effects these measures have on the fleet-wide CO_2 reduction potential.

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Appendix

Besides the consultation of aviation analysts and representatives of major aircraft manufacturers, the following Internet pages were consulted for the estimation of the rates of fuel efficiency improvement of the next-generation aircraft types for the BAD, BASIC, and BEST scenarios as well as the associated production ramp-ups.

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