Fuel-based flight inefficiency through the lens of different airlines and route characteristics

A post-operational analysis for one day of traffic at the ECAC area.

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***Abstract*—In the light of the ambitious environmental targets for future air traffic management paradigms, there is a need in the enhancement of current (key) performance indicators, with the objective to facilitate the identification of different sources of environmental inefficiencies, and to enable large scale and systematic post-operational analyses. Based on a previously published methodological framework to compute fuel-based performance indicators, this paper aims at exploring these inefficiencies at different granularity of the results. For this purpose, a set of filters has been applied on a data-set of 24h of traffic within the ECAC (European Civil Aviation Conference) area, encompassing different airspace users categories, route length and flight frequencies. The results show that the carriers prone to low-cost business models have, on average, the highest value of total fuel inefficiency in absolute terms with a median around 530 kg (17%); compared to full-service carriers with a median around 432 kg (20%); observing as well that relative fuel inefficiency significantly drops as the stage length of the routes increases. Moreover, results reveal that the busiest the routes are, the higher fuel inefficiencies they accrue. For routes with less than 5 departures per day, the fuel inefficiency accounts for 19.1% in relative terms, if compared with the total fuel burnt; whereas for the routes from the category between 12 and 20 daily departures the relative fuel inefficiency rises to 22.6%. These figures are obtained when the reference trajectory used to derive fuel inefficiency is a full free route trajectory at maximum range operations and without considering en-route charges. The paper also explores other reference trajectories, constrained to the airway network in force and/or considering the (estimated) cost index chosen by the airspace users. It is acknowledged, however, that a larger data-set needs to be considered in the future to generalise the validity of the obtained results.**

Keywords—fuel-based flight efficiency; post-ops; environmental impact; route length; flight frequency; AUs categories

I. INTRODUCTION

The environmental concerns of the aviation sector becomes an urgent issue in the light of the increasing pressure to reduce global CO_2 emissions. The recent report published by the International Council on Clean Transportation (ICCT) estimates that aviation contributes to 2.4% in global CO_2 emissions from fossil fuel use indicating a 32% increase over the past five years [1]. Such a rapid increase in greenhouse gas emissions imposed a burden of challenges not only to airlines, but also to regulatory bodies to stifle their further growth and promote policies to support sustainable and green aviation.

The new concepts and solutions underpinned by the ATM modernisation programs, such as SESAR in Europe and NextGen in the U.S, aim to gradually contribute to the elimination of environmental inefficiencies as one of the major goals. For example, SESAR set up a high level ambition which aims to reduce the additional gate-to-gate flight time per flight and gate-to-gate CO_2 emissions to reach maximum relative improvements by 55% and 10% respectively by 2035 in comparison to baseline scenario (2012) [2]. The latter corresponds to the reduction in average CO_2 emissions per flight of 0.8-1.6 tonnes. Therefore, the performance of new ATM concepts and solutions with respect to environmental goals (and other ATM objectives in general) need to be constantly assessed in order to identify the potential gaps between actual and high-level targets and to indicate the corrective actions which need to be performed in order to close this gap.

Developed in line with the ICAO framework to assess ATM performance [3], the Single European Sky (SES) programme defines European Union-wide and local performance targets and a framework to monitor them referred as the SES Performance Scheme. Similar frameworks are proposed by the Fedearl Aviation Administraiton (FAA) and the Civil Air Navigation Services Organization (CANSO). In general, these frameworks apply key performance indicators (KPIs) which measure horizontal flight efficiency by comparing flight plans or actual trajectories flown against the great circle distance (i.e. the shortest *ground* distance in a sphere). In this way, the effect of vertical (and speed) flight inefficiency on the environment is totally neglected, and weather conditions (mostly wind fields) are not taken into account to determine the shortest *air* distance, which would lead to a more accurate reference to measure flight inefficiencies. In turn, the SESAR 2020 Performance Framework [4] defines some PIs in order to facilitate the pre-operational assessment of certain SESAR solution scenarios. These scenarios are typically simulated and thus, fuel figures are already an output of the simulation tools used for these validations.

Ref. [5] was one of the pioneering works that focused on post-operational analysis by measuring the fuel differences between the executed trajectories and a reference trajectory. Extending the previous work, [6] proposed some total airspace user (AU) cost efficiency indicators for post-operational analysis too, with a case study encompassing approximately 1,500 trajectories. A similar approach was proposed in [7], in which the importance of changing the reference trajectory is analysed in order to obtain different layers of flight (in)efficiency. It is worth emphasising, however, that inefficiencies for the AU are not necessarily the same inefficiencies for the environment.

In this context, [8] proposed an approach in deriving post-operational flight efficiency PIs involving a variety of reference trajectories that enabled to capture different sources or components of the flight inefficiency. This paper is founded on this methodological framework, extending the previous study –performed at the FABEC (Functional Airspace Block Europe Central) level– by applying a set of filters which may shed light on flight efficiency derived at different levels of data aggregation, and analysing a full day of operations, this time, at ECAC level. Furthermore, the paper analyses the inefficiency of different airline categories with respect to several reference trajectories and by decomposing the flight inefficiency across different time-frames (i.e., strategic, tactical or both). Different reference trajectories have been selected and analysed in order to understand how close is the behaviour of different airline groups towards environmentally friendly operations. Secondly, the analysis of routes with different length is performed to capture their potential differences in terms of fuel inefficiency. Finally, the routes with high-frequency connections are analysed with the aim to identify whether the inefficiency of these routes is generally higher than the inefficiency of routes with small and medium frequencies.

II. Methodological background

The fuel-based PIs used in this study are aimed to assess fuel inefficiencies from post-operational data. For the sake of a greater traceability and better interpretability of the results obtained, a brief description of the main methodology proposed by Prats et al. [8] is provided below. Then, section II-B aims to explain the rationale behind the selection of different filters that will drive the analysis of this paper.

A. Overall methodology for fuel-based PIs computation

Fig. 1 shows a block diagram summarising the methodology used in this paper. The performance analyser is the core module of the given framework, which receives a set of historical trajectories subject to study and implements all the fuel-based PIs; including, as well, some indicators from the current Performance Scheme for benchmarking purposes. Two types of historical trajectories are used for the assessment: the last filed flight plan and the actual trajectory flown. Yet, aiming at applying this methodology in the future, the following nomenclature, aligned with the SESAR trajectory based operations (TBO) concept [9], is used in this paper: RBT (reference business trajectory), which is the trajectory that has been agreed to fly by all concerned stakeholders after the negotiation process with the Network Manager, applying (if necessary) air traffic flow management (ATFM) regulations; and the executed trajectory, which contains updates at tactical level on the RBT (if any), for instance due to air traffic control (ATC) interventions.

The reconstruction of these trajectories is based on complex estimation procedures and techniques ([7], [10]) which require additionally an aircraft performance model (such as specific fuel consumption parameters and aerodynamic coefficients); and the historical weather conditions encountered by the flight. Once the given trajectories are fully reconstructed, they will be compared with optimal trajectories specifically computed by an independent module (B trajectories in Fig. 1). This module enables the configuration of different optimization criteria and/or constraints, leading consequently to different optimal trajectories.

For example, the optimal trajectory can be computed assuming a full free route airspace, or constrained to current air traffic services (ATS) routes. It can be computed assuming maximum range operations (i.e. minimizing fuel), or by fixing the cost index (CI) selected by the airspace user (AU). This optimal trajectory can also be computed by fixing the horizontal track followed by the RBT or the executed trajectory, capturing in this way, only horizontal inefficiencies. By combining, on the one hand, the reconstruction of historical RBT or executed RBT (*A* arrow in Fig. 1); and on the other hand, the different reference trajectories (*B* arrows), a set of nine fuel-based PIs are proposed:

$$\begin{aligned}
\Delta F_T &= \hat{F}_e - F^* & \Delta F_T^h &= F_e^* - F^* \\
\Delta F_T^v &= \Delta F_T - \Delta F_T^h & \Delta F_S &= \hat{F}_{RBT} - F^* \\
\Delta F_S^h &= F_{RBT}^* - F^* & \Delta F_S^v &= \Delta F_S - \Delta F_S^h \\
\Delta F_t &= \hat{F}_e - \hat{F}_{RBT} & \Delta F_t^h &= F_e^* - F_{RBT}^* \\
\Delta F_t^v &= \Delta F_t - \Delta F_t^h,
\end{aligned} \tag{1}$$

where ΔF_T is the total fuel inefficiency caused by all ATM layers, computed as the difference of the estimated fuel of the executed trajectory($\hat{F}_e$) and the fuel of the optimal trajectory for that particular flight (F^*). ΔF_T^h captures the fuel inefficiency due to all ATM layers only in the horizontal domain, regardless of how (in)efficient the vertical/speed trajectory profile was. This is achieved by comparing the fuel consumption of the best trajectory one could fly if following the execution route (i.e., optimizing the vertical/speed profile while fixing as constraint in the optimization process the executed route, F_e^*); and the fuel consumption of the optimal 4D trajectory. ΔF_T^v, in turn, captures the inefficiencies due to all ATM layers only in the vertical/speed domain, regardless of how (in)efficient the horizontal trajectory was. Similarly, ΔF_S and ΔF_t are the PIs capturing the total fuel inefficiency of, respectively, the strategic and tactical layers of the ATM; ΔF_S^h and ΔF_t^h are the PIs capturing the inefficiency in the horizontal trajectory

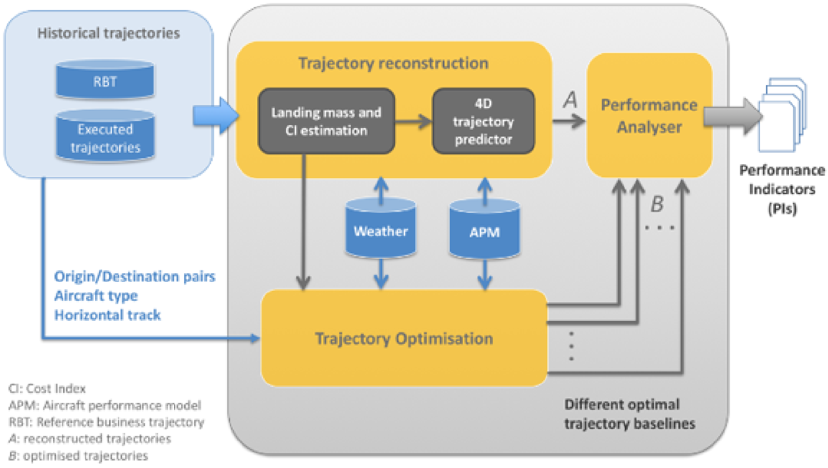


Fig. 1: Methodology to compute the environmental Performance Indicators (PIs) (Source: [8])

of, respectively, the strategic and tactical layers; and ΔF_S^v and ΔF_t^v are the PIs capturing the inefficiency in the vertical/speed profiles of, respectively, the strategic and tactical layers.

As seen in equations (1), strategic inefficiencies can be computed by estimating the fuel consumption of the RBT trajectory ($\hat{F}_{RBT}$) and/or the fuel consumption of the best trajectory one could fly if following the RBT route(F^*_{RBT}), i.e., optimizing the vertical/speed profile while fixing as constraint the RBT route. Since the RBT is used for these indicators (and not the first submitted SBT), these indicators also capture the inefficiencies due to ATFM measures, if any.

One has to acknowledge the limitation of this methodology which resides in the error in all these indicators caused by estimation of the mass of the aircraft, which is required to estimate fuel consumption from historical data, but also to generate the optimal reference trajectories. In this paper, it is assumed that all aircraft land at the 90% of their maximum landing mass. Further work will incorporate a mass estimation module implementing, for instance, the approach proposed in [11]. Similarly, the error in the estimation of the CI from historical tracks will also affect the accuracy of these PIs.

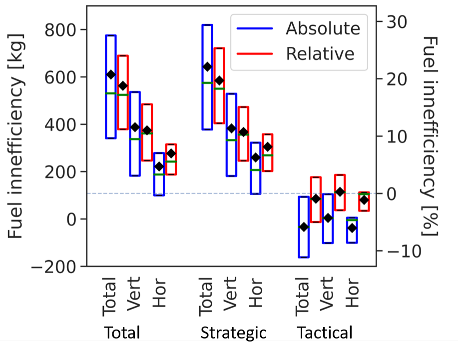
B. Selection of the filters employed

As mentioned earlier, some filters are proposed in this paper aiming at providing a valuable insight into the flight inefficiency across different categories.

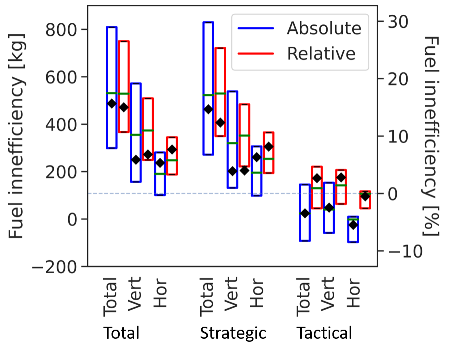
1) Airline business models: Airline operators intend to plan the most efficient route according to their underlying business policy. Provision of a straightforward definition of airline business models and their major distinction elements is not an easy task due to the extremely dynamic nature of the industry. The traditional classification of low-cost (LCCs) and full-service carriers (FSCs) appears to be ambiguous in the light of a highly competitive environment and generally low-profit margin airline industry. The trend of convergence which entails a process of standardization and homogenization based on diffusion of knowledge is a fundamental part of the competitive process [12].

The given trend may have tremendous implications on airline cost structure which can be further directly translated into the generation of the optimal trajectory. The analysis aims to capture whether the process of airline business hybridization may be reflected into the sphere of fuel inefficiency and to observe to which extent the performance of different airline categories may vary in flight inefficiency with respect to different reference trajectories. For this purpose, the results of the recent study of Magdalina and Bouzaima [13] on the clustering process of the European airlines were applied as a filter in our analysis. The study used data from 49 European airlines that are eventually grouped into four business models: FSC, LCC, and two separate hybrid models (Hybrid 1 & Hybrid 2; H1 & H2). The obtained clusters are adopted and applied for further analysis.

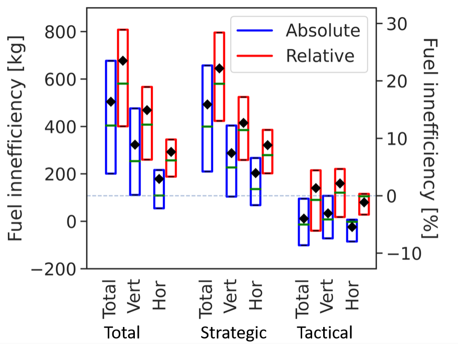
2) Route lengths: The length of the route highly affects the total airline cost structure, because with an increase in the average route length, important variable costs (i.e., fuel, staff and maintenance) increase [14]. Moreover, the average route length of an airline has a negative effect on the total cost of the airline which clearly demonstrates the existence of economies of stage length ([15], [16]). In this vein, the shorter routes will have less opportunity to absorb the negative effect of the potential deviation from a planned trajectory across the flight execution. Thus, the potential discrepancy between actual and planned trajectories may eventually result in higher fuel consumption and excessive fuel inefficiency. In order to observe if there is difference across the routes with different length, the analysis will split the routes in five different categories. The categories are tailored to realistically reflect the network structure of the carriers operating at the ECAC level. With all the previous considerations, the fuel-based flight inefficiency is analysed across the following route length categories: $(0, 350]$, $(350, 675]$, $(675, 1000]$, $(1000, 1500]$, $(1500, \infty)$ NM.



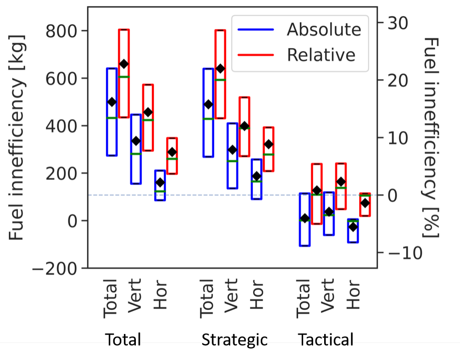
((a)) LCC group



((b)) H1 group



((c)) H2 group



((d)) FSC group

Fig. 2: Fuel inefficiencies for four airline categories based on their business models (Reference trajectory assuming a full free-route airspace, no en-route charges, flight level allocation and orientation schemes, and maximum range operations).

3) Route frequencies: The European network is characterised by a sufficiently large number of the routes with very high frequency. For instance, in February 2020 there were many high-frequency connections in the European network: 157 short- and medium-haul airport pairs had 12 or more flights per day (total of both directions) [17]. It often entails that an aircraft will operate the same route several times in a 24-hour period. Moreover, one delay on a high-frequency route will have a substantial impact on a subsequent rotation which could impose an additional burden on total costs. In this way, the airline may opt to operate the routes which are non-optimal in terms of fuel consumption in order to compensate for the delay propagation in their networks. In order to observe if there is a distinct behavior across the routes with different frequencies with respect to fuel-based flight inefficiency, the following four route frequency categories are analysed in this paper: $(0, 5], (5, 12], (12, 20], (20, \infty)$ departures per day.

III. Results

The results are based on the analysis of the sets of 24h of historical flown and planned trajectories for July 28th 2016 (high demand scenario). These trajectories were reconstructed from the following data extracted from Eurocontrol's DDR2 (demand data reposotory): last filed flight plans submitted by the AU (DDR2 M1 type file); and correlated position reports from different surveillance sources coming from the Eurocontrol member states (DDR2 M3 type file).

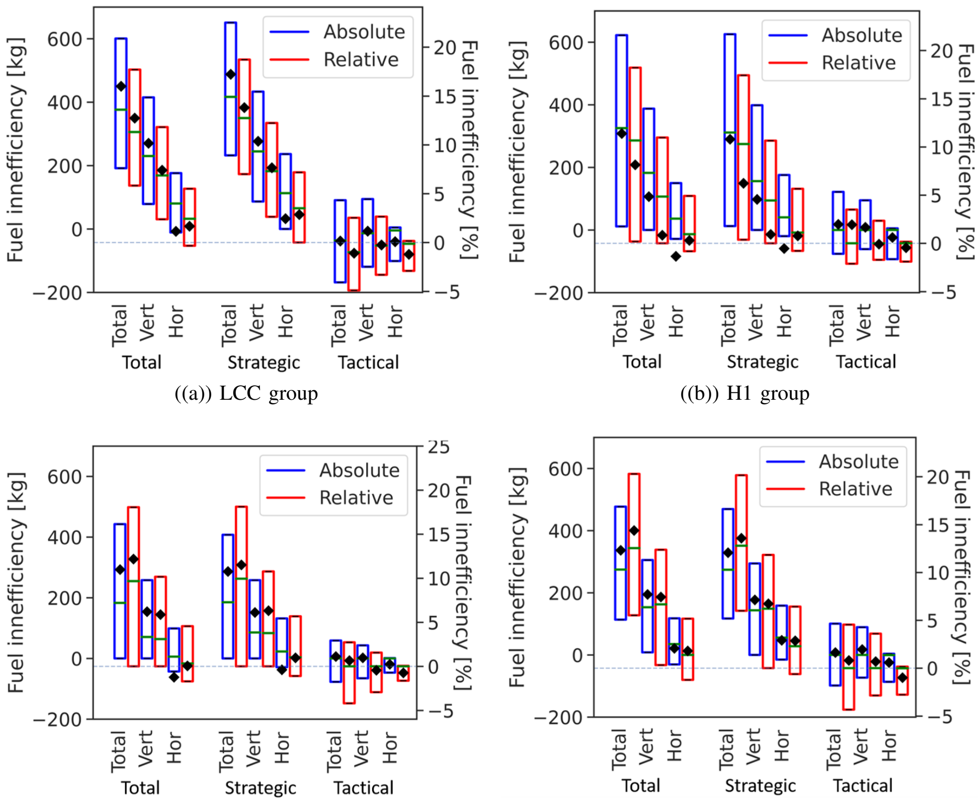
As mentioned earlier, these sets of trajectories are referred in this paper as, respectively, the RBT and executed trajectory (or executed RBT). For a more detailed information on the dataset used, please refer to [8]. When computing the fuel/distance of both trajectories (A and B in Fig. 1) we exclude the segments of the trajectory within a 40NM radius around the origin/destination airports. This is the same practice done by the SES indicators.

Results are shown in box plots, representing the fuel inefficiency with respect to a reference trajectory (B trajectory in Fig. 1). For each PI in the figures below, the average (diamond), the median (horizontal line) and the first and third quartiles (bottom and top edges of the box) are given for absolute (blue) and relative (red) inefficiencies.

A. Inefficiencies with respect to different airline categories

Figs. 2 and 3 display the breakdown of the fuel efficiency across different airline categories and different ATM layers.

In Fig. 2, the optimal trajectory used as a reference is computed assuming a full free-route airspace, current flight level allocation and orientation schemes, no en-route charges and



((a)) LCC group

((b)) H1 group

((c)) H2 group

((d)) FSC group

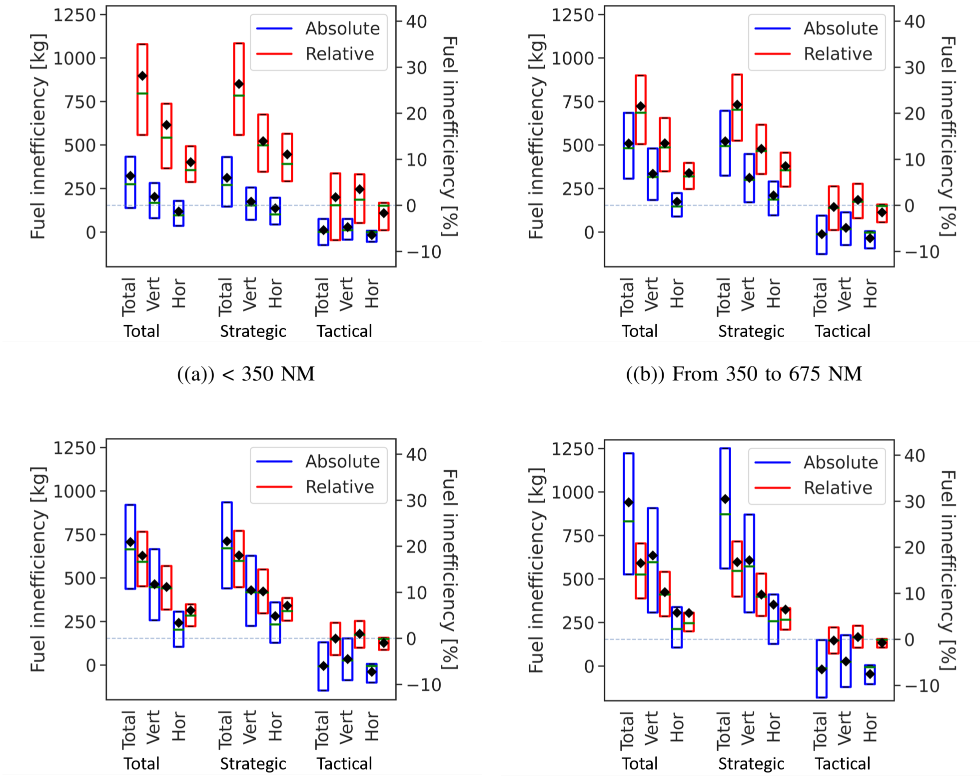
Fig. 3: Fuel inefficiencies for four airline categories based on their business models (Reference trajectory constrained to the current structured ATS en-route network, flight level allocation and orientation schemes, and maximum range operations)

maximum range operations (i.e. Cost Index zero). Conversely, Fig. 3 shows the same PIs but with the reference (optimal) trajectory computed in the same conditions as above, but constrained to the ATS en-route network enforced for the day of operations (structured routes).

It is worth mentioning that we optimise free-route from origin airport ARP (airport reference point) to destination airport ARP. Terminal areas are not considered because the main focus is on the en-route phase. For the structured routes optimisation, the data to generate the route network is also obtained from DDR2.

1) Free route and maximum range as reference trajectory (FR CI-0): As seen in Fig. 2, it seems that there is a substantial difference between the four airline groups in terms of the total fuel inefficiency. The carriers from H1 and LCC groups have the highest total inefficiency in absolute terms with a median around 530 kg. However, the carriers from these two groups are more fuel efficient compared to the two other groups in relative terms - both groups have a relative fuel inefficiency of around 17%. On the other hand, the carriers from FSC and H2 groups appear to have a slightly better performance in terms of absolute total fuel inefficiency with a median around 432 kg and 403 kg respectively (representing around 20% in relative terms in both groups). As observed from Fig. 1, the inefficiency incurred mainly stems from the strategic part of the ATM for all four airline categories. The finding indicates that carriers from groups of H1 and LCC might have their respective RBTs closer to the reference trajectories as reflected by their lower values of fuel inefficiency in relative terms.

On the other hand, at tactical level we see that route inefficiencies are, in general, close to zero, across all four airline groups indicating that the ATC is providing a shortcut for most of the flights. Among them, the LCC group has the highest negative “total inefficiency” with median of -33.9 kg (-0.96%), followed by the carriers from H2 group with a median around -13.8 kg (corresponding to the -0.73% in relative terms). It is interesting to observe that the carriers from the H1 and FSC groups have the highest value of total tactical fuel inefficiency with a median of around 24 kg (0.9%) and 1 kg (0.03%) respectively. In the case of the FSC group, the given results might be explained by the fact that they operate extensive hub-and-spoke networks mainly connecting secondary airports with hub airports which leaves less opportunities for ATM tactical interventions and possible shortcuts. In the case of the H1 group, the airlines also operate a hub-and-spoke network but with low level of flight frequency and at less congested hubs, which probably allows more maneuvering space for potential fuel savings than in the case of the FSC group.



((a)) < 350 NM

((b)) From 350 to 675 NM

((c)) From 675 to 1000 NM

((d)) From 1000 to 1500 NM

Fig. 4: Fuel inefficiencies for different route lengths (Reference trajectory assuming a full free-route airspace, no en-route charges, flight level allocation and orientation schemes, and maximum range operations)

It is worth mentioning that across all airline categories, vertical inefficiencies are higher than horizontal inefficiency at both the strategic level and the tactical level. In relative terms, the vertical inefficiency at strategic level is slightly lower at the LCC and H1 groups compared to FSC and H2 groups. This could be explained by the fact that those airlines typically operate in congested airspace, where optimal cruise altitudes cannot always be granted by the ATC to all flights. Moreover, the tactical layer provides some fuel efficiency gains at the horizontal domain due to ATC shortcuts.

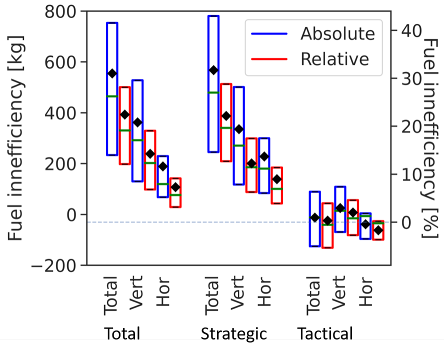
2) Structured routes and maximum range as reference trajectory (SR CI-0): Not surprisingly, the results reveal that the total fuel inefficiency is generally lower if the optimal trajectory on the structured ATS en-route network is considered as a reference trajectory, if compared to the free route reference, as the former one better reflects the real operational environment of the day of study.

The results indicate that if the optimal trajectory is constrained to ATS route, the difference between different airline groups is even more pronounced in terms of the absolute total fuel inefficiency compared to the full free route reference. As observed from Fig. 3, the H2 group has a median of around 183 kg (around 9.6%) which presents the best performance among the four airline groups. On the other hand, the carriers from the LCC group exert the highest absolute total fuel inefficiency with a median of around 376 kg (11.3%). The median in total fuel inefficiency for the FSC and H1 groups accounts for around 275 kg (12.5%) and 325 kg (10.6%) respectively. Irrespective of the median value of flight inefficiency across airline groups, it is interesting to observe that there is a large dispersion in the total fuel inefficiency (both in the vertical and horizontal domain) particularly for the H1 and H2 groups. This might be attributable to the fact that the carriers within these two groups operate different networks and their business models are somewhere between "pure" LCC and FSC which may have a direct implications to fuel efficiency.

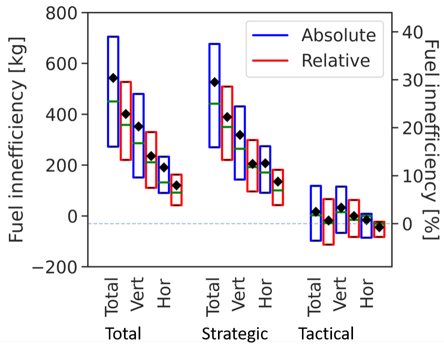
As in the previous case, the total inefficiency is mainly induced at strategic level, particularly by its vertical component which median ranges from 244 kg (7.3%) for the LCC group, to 85 kg (3.8%) for the H2 group. This clearly indicates that there is still a substantial difference between vertical profile of the RBT trajectory and the optimal one.

B. *Inefficiencies with respect to different route stage lengths*

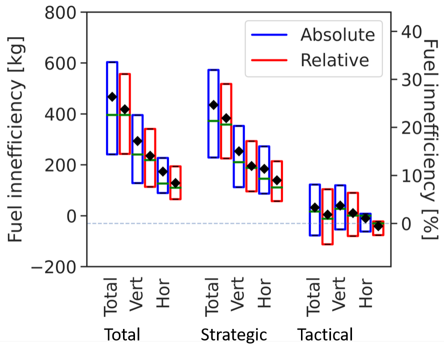
The breakdown of the fuel efficiency across different stage lengths is analysed here. The data analysis shows that 36.8% of the routes operated within the ECAC level are less than 350 NM, 30.5% of the routes fall in the range between 350 NM



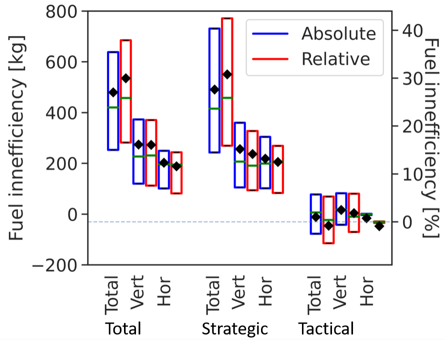
((a)) Freqx < 5 times



((b)) Freq betw 5 and 12 times



((c)) Freq betw 12 and 20 times



((d)) Freq betw 20 and 30 times

Fig. 5: Fuel inefficiencies for different route frequency categories (Reference trajectory assuming a full free-route airspace, no en-route charges, flight level allocation and orientation schemes, and maximum range operations)

and 675 NM, while the rest of the flights (32.8%) have the length which is over 675 NM. Within the latter category, 19% of the flights are between 675 NM and 1000 NM, while those between 1000 NM and 1500 NM encompasses only 11.6%. Finally, the flights which are longer than 1500 NM constitute around 2% of total traffic.

As in previous section, the results are derived for two families of reference trajectories: assuming a full free route scenario and constraining the optimisation to the available ATS network. Both references are computed considering current flight level allocation and orientation schemes, maximum range operations (i.e. Cost Index zero) and not considering en-route charges.

1) Free route and maximum range as reference trajectory (FR CI-0): The results presented in Fig. 4, clearly indicate that there is a great difference in the flight inefficiency among the routes with different stage lengths. Not surprisingly, the results show that longer routes exhibit higher inefficiency in absolute terms. Conversely, the relative errors in inefficiency significantly drop as the stage length of the routes increases. For instance, the total inefficiency for the short routes that are less than 350 NM has a median around 274 kg corresponding to very high relative error of around 24.2%. On the other hand, flights in the categories of the route length between 675 and 1000 NM and 1000 and 1500 NM have larger median of around 665 kg and 831 kg respectively, which corresponds to relative inefficiency of around 16.6% and 14.0%. As previously observed, the large portion of the total inefficiency is generated at the ATM strategic level as the AU are obliged to use a structured ATS en-route network, rather than free route airspace which is assumed as an underlying reference trajectory. Moreover, a substantially large dispersion in absolute total inefficiency is observed for the category between 1000 and 1500 NM compared to other groups.

At tactical level, results show that there are no significant differences among the given groups with respect to both the absolute and relative values in the total fuel inefficiency. The total tactical inefficiency for all is, in general, negative, meaning that the ATC is short-cutting most of the flights, although some positive vertical flight inefficiencies are still present. It is interesting to observe that the tactical layer contributes to the horizontal efficiency gains which are very similar in relative terms across the different categories (accounting for around -0.1%). Contrary, there is a small inefficiency in vertical domain which is consistent across the four groups.

2) Structured routes and maximum range as reference trajectory (SR CI-0): Overall, the results of the analysis show the similar behaviour as in the previous case, although the relative and absolute errors of fuel inefficiency in each respective category are substantially lower than in the case when the optimal trajectory assumes a full free-route airspace. Due to space limitations, these figures are not included in the text, although they show the similar trend as in Fig. 4: the total fuel inefficiency of the flights in the categories of the route length less than 350 NM and between 675 NM and 1000 NM have median of around 118 kg (17.3%) and 301 kg (9.1%). The large dispersion in fuel inefficiency is observed among the flights in the category of the route length between 1000 and 1500 NM with the median of 663 kg (11.3%.)

C. Inefficiencies with respect to different route frequencies

This section presents some illustrative results for fuel inefficiency across different route frequency categories. At this stage, we were focused on capturing the difference in fuel inefficiency among different route categories with respect to the total frequency and not considering the airline operating the specific route.

1) Free route and maximum range as reference trajectory (FR CI-0): Fuel-based flight inefficiencies across routes with different frequencies are given in Fig. 5. As observed, there is not substantial difference in the absolute figures across different route frequency categories. For instance, the total inefficiency has a median around 400 kg for all four categories, mostly due to the strategic part of the ATM. However, the results clearly indicate that there are considerable differences across the four categories in relative terms. Generally, the busiest the routes are, the higher inefficiencies they accrue. For the routes that have less than 5 departures per day, the inefficiency accounts for 19.1% in relative terms if compared with the total fuel burnt, whereas for the routes from the category between 12 and 20 daily departures the relative inefficiency rises to 22.6%. Finally, the routes with very high daily frequencies (between 20 and 30 departures per day) face a very high inefficiency which goes to more than 25% in relative terms.

Given the fact that the reference trajectory is constrained to free route airspace which is already implemented in some parts of the ECAC and the U.S, the results obtained provide a solid indication that may help the stakeholders to better accommodate their operation to the new operational environment.

2) Structured route and maximum range as reference trajectory (SR CI-0): Similarly to the previous case, the results here follow the same pattern – the high frequency routes accrue the higher fuel inefficiency in relative terms. Compared to previous case, the total fuel inefficiency is lower, accounting for on average, around 200 kg.

Given the fact that the reference trajectory is constrained to ATS routes, which is close to the real operation environment of the day of study, the results obtained provide a solid indication that the busiest route may require a more careful approach during the flight planning process in order to close the large gap between RBT and the optimal trajectory. These actions will eventually contribute to better environmental performance of the flights.

D. Detailed analysis for high frequency routes

This section aims to further elaborate the total fuel inefficiency of high frequency routes as those featured with the greatest fuel inefficiency in relative terms. Total fuel-based flight inefficiencies are analysed for high density routes which had more than 20 flights per day. The average length of these routes has a median of 278 NM. These connections were largely domestic, connecting the major capital cities (e.g., Munich (EDDM) - Berlin (EDDT), Madrid (LEMD) - Barcelona (LEBL), Istanbul (LTBA) - Izmir (LTBJ), Rome (LIRF) - Milan (LIML), etc.); or connecting major capital cities and tourist destinations (e.g., Madrid (LEMD) - Palma de Mallorca (LEPA), Istanbul (LTBA) - Antalya (LTAI), etc.). A total of 23 routes with the frequencies higher than 20 have been extracted from our database.

In addition to the two previous trajectory references (FR CI-0 and SR CI-0), this analysis also includes two other reference trajectories that use the CI estimated from the executed trajectory (i.e. the CI chosen by the AU) to compute the reference trajectory (FR CI-AU and SR CI-AU). The results are depicted in Fig. 6, where the *whiskers* above (below) the boxes in the figure represent the third (first) quartile plus (minus) 1.5 the inter-quartile range of the distribution.

1) Free route and maximum range as reference trajectory (FR CI-0): The results will be discussed first with respect to FR CI-0 as the reference trajectories. The average in absolute and relative terms is used for discussion. Interestingly, the routes within Turkey are those with the highest value of total flight inefficiency which goes from approximately 683 kg (47.8%) (for Istanbul Sabiha (LTFJ) - Bodrum (LTFE)), up to 1143 kg (82.3%) (for Istanbul Sabiha (LTFJ) - Izmir (LTBJ)).

The second set of the routes which have considerably high flight inefficiency encompassing the flights that connect the capital cities with the touristic destinations within Spain – i.e., Madrid (LEMD) - Palma de Mallorca (LEPA), with the total fuel inefficiency of around 530 kg (27.9%)– and Italy – i.e., Catania (LICC) - Rome (LIRF), with the total fuel inefficiency of around 523 kg (27.4%). The routes that exert the similar fuel inefficiencies are those connecting two major capital cities such as Berlin (EDDT) - Munich (EDDM), with the flight inefficiency of around 480kg (28.8%); and London (EGLL) - Dublin (EIDW) with the flight inefficiency of around 408 kg (24%). Finally, the routes with the less fuel inefficiency are those operated within Italy –i.e., Milan (LIML) - Rome (LIRF), with the fuel inefficiency of 254 kg (19.5%)– and within Portugal –i.e., Lisbon (LPPT) - Porto (LPPR), with the fuel inefficiency of around 81 kg (10.0%). It is interesting to observe that the actual route flown between Barcelona (LEBL) and Palma de Mallorca (LEPA) almost coincides with the optimal reference trajectory, since the respective flight inefficiency equals to almost to zero.

2) Structured route and maximum range as reference trajectory (SR CI-0): Yet, even if the optimal trajectory is constrained to structured routes, some fuel inefficiency is still present, although substantially lower than in the previous

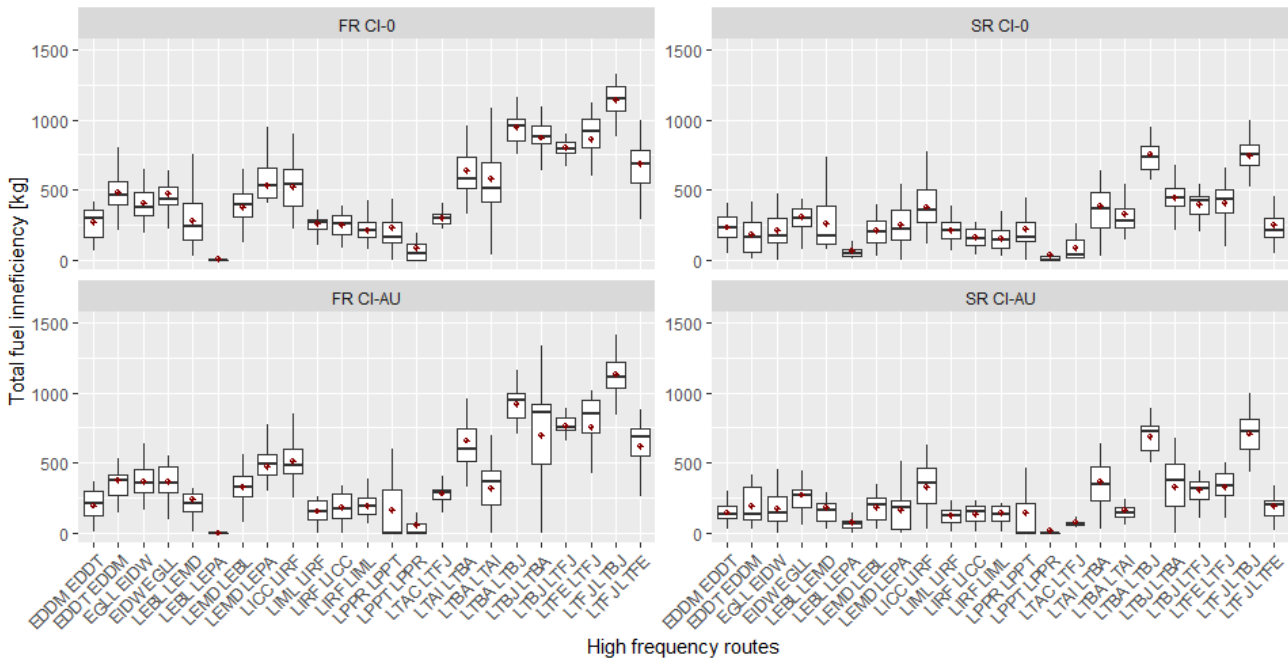


Fig. 6: Fuel inefficiencies for routes with a high frequency

case. It is worth noting that most of these routes are short-haul (36.8%) and thus operate mainly within the same ANSP surveillance. It further implies that the fuel inefficiency might mainly stem from the fact that the AUs are not (or cannot) planning their trajectories by using the best route sequence in the network or flying non-optimal flight levels. Some routes perform substantially better than the others in terms of the fuel inefficiency when a SR CI-0 is considered. For instance, with the given constraints, the route such as Lisbon (LPPT) - Porto (LPPR), Barcelona (LEBL) - Palma de Mallorca (LEPA) and Ankara (LTAC) - Istanbul Sabiha (LTFJ) perform very well with an average flight inefficiency around 30.9 kg (3.53%), 61.4 kg (7.39%) and 83.4 kg (7.92%) respectively.

3) Structured route and the CI estimated from the executed trajectory as reference trajectory (SR CI-AU): Airlines typically tend to apply higher CI values other than zero to reduce block times. The decision highly depends on the airline business models and very often on the status of a specific flight (e.g., connecting flight experiencing delay, the final flight of the day affected by a curfew, etc.). Thus, it is clear that the previous PIs (SR CI-0 and FR CI-0) also encounter for the AU "induced" inefficiency (i.e. their decision to fly faster). Considering SR CI-AU as a reference trajectory, our attempt is to remove the AU-induced inefficiency in order to isolate as much as possible the ATM-induced inefficiency.

For instance, the inefficiencies for the routes between Istanbul (LTBA) to Antalya (LTAI), Izmir (LTBJ) and Istanbul (LTBA) and Munich (EDDM) and Berlin (EDDT) go down to approximately 161 kg (7.1%), 323 kg (16.1%) and 145 kg (8.2%), respectively, in the case of SR CI-AU instead of 323 kg (14.9%), 446 kg (23%) and 234 kg (13.9%) found in the case of SR CI-0. In other words, by using the AU planned CI to compute the reference trajectory, the high frequency routes from the set induce an average inefficiency of around 56 kg less representing approximately a 5.3% increase in relative terms. This difference could be directly attributable to AUs' inefficiency and not to ATM inefficiency.

IV. Conclusions

At a time when aviation is challenged by the ongoing regulations towards a more carbon-neutral aviation, it is reasonable to expect that the low-carbon emission trajectory will receive greater focus from operators in the future. Flight efficiency is also relevant in the present time, when the crisis derived by the COVID19 pandemic is struggling the economic income of the airlines. This paper aims to demonstrate the benefits of the methodology which employs advanced parameter estimation and trajectory optimization techniques to build fuel-based flight inefficiency performance indicators for post-operational analysis. The preliminary results shown here provide in-depth insight into the fuel inefficiency with respect to different operational features (i.e. flight characteristics) encompassing route length, frequencies and AUs categories.

The conclusions are purely data-driven, which can serve as a valuable input for setting up the ambition targets for key performance indicators which are very often provisional or based on the assessment of experts' judgement. The fuel-based flight inefficiency observed across AUs categories when different optimal trajectories are used may help AUs to better understand the consequences of flying non-optimal routes. In addition, the results when the reference trajectory assumes a full free-route airspace may facilitate the assessment of the benefits directly derived from flying in free-route airspace as this concept is envisioned to be extensively deployed in the future global ATM system. In this context, the given results provide solid evidence of the direct operational benefits which can be derived by deploying free route airspace at the ECAC level. Having in mind that different types of AUs have different business models in place, the operational saving in fuel consumption by flying in free-route airspace may have different implications on their respective cost structures, as fuel inefficiency can be easily monetised. The similar conclusion can be drawn for fuel inefficiency across routes with different frequencies. In particular, the high fuel inefficiency of the routes with high-frequency connections (largely domestic, or between major capital cities) may provide an alert to policy makers and ANSPs to consider appropriate counter-measures to mitigate the environmental impact of these flights.

As future work, the analysis could be tailored to encounter any specific flight characteristics. This is particularly useful to analyse the flight inefficiency with respect to certain areas of interest, like seasonality, geographical scope or other functional airspace areas. In this sense, the presented results focused on a specific use case of interest and on the given day of operation. Although the methodology allows for many days, the computational resources needed are not negligible and thus our initial attempt was to confine the analysis on the single operational day. In order to validate commonalities and trends of the results obtained, we are currently working on a full-scale system that allows to digest a batch of days. This will provide a solid foundation to proceed with the specification of multiple regression models designed for different time-frames and different ATM layers. This further implies that a different set of explanatory variables will be chosen for each regression model. A model to capture strategic inefficiencies could include more "general" variables, whereas a model for tactical ones must capture the actual disturbances that are not accounted for at strategic level (e.g., weather, flow regulations, etc.). The particular inspiration for this can be found in the recent paper [18], where causal relations among en-route inefficiency are explored with multiple variables (e.g., convective weather, wind, miles-in-trail restrictions, etc.).

Finally, analysts have to bear in mind the limitations and drawbacks of the methodology used which mainly reside in uncertainty in the aircraft performance and estimation of mass and CI. The further advancement in these methodologies will contribute to better accuracy of the results.

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