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Fuel flow analysis for the cruise phase of commercial aircraft on domestic routes

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ABSTRACT

From the point of view of the environmental impact of aviation, rather than fundamental strategies mainly intended for lower fuel consumption, and thereby less carbon dioxide emissions, more comprehensive approaches have emerged as climate optimized flight concepts, which promise potentially better strategies due to consideration of the tradeoff elements in a broader sense. Since climate optimized flight concepts introduce dynamic flight parameters for the best tradeoffs between economic and environmental indicators, defining the effect of these parameters on fuel consumption becomes ever more crucial. In this context, this study develops empirical equations for the cruise phase fuel flow which could be used to better understand fuel consumption. Major domestic routes in Turkey and the most frequently used narrow body commercial aircraft are investigated. The empirical equations are generated using actual flight data of 3857 flights (4320 cruise observations) performed by A319/320/321 and B737/B738 in Turkish air space. All of the flight data are obtained from the national flag carrier airline of Turkey, Turkish Airlines. According to the results, the effects of three main performance parameters, cruise altitude, mass and speed on the fuel flow, are characterized. The results show the amount of inefficient fuel usage through the carriage of unnecessary mass, departing from the optimum cruise altitude or expediting cruise flight.

1. Introduction

Recently, there has been a tradeoff challenge growing between economic and climate impact resulting from the output of economic progress and growth demand. Despite improvements in the efficiency of industrial systems, every percentage increase in economic key performance parameters brings an increase in climate impact due to an unequal progress favoring economic growth demand. In addition to legislation dedicated to environmental protection, other industries have more flexible options (i.e., switching to alternative fuels, less weight concerns, ground base operations and relatively lower safety and backup necessities), while aviation has more specific constraints which make it difficult to run the required tradeoff to reduce climate impact. Also, since aviation is a key industry helping to steer the economy, it is more resistant with respect to environmental considerations.

Currently, two main mutually linked concerns related to air transportation exist, namely efficiency and environmental impact. Efficiency involves parameters such as fuel consumption, time, and optimum utilization of airport and terminal area resources (i.e., slots, direct routing and continuous descent operations), while emissions and noise are associated with environmental impact. Despite significant improvements in airframe and engine design, increases in fuel price and inefficient air traffic management due to capacity problems lead to a considerable decrease in flight efficiency (i.e., fuel or time cost), thereby increasing emissions.

There are a number of elements affecting the fuel consumption of a typical flight, such as cruise altitude and speed, mass, weather conditions or air traffic management. In addition, the difficulties controlling these variables make the measurement of the effect size of each variable a challenge. However, there have been numerous studies (such as those focusing on environmental and/or economic aspects) which require measurement of the sole effect of a single variable on fuel consumption. Moreover, each flight phase presents different levels of saving in fuel consumption, while

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creating counter results, such as capacity, time cost, noise and contrail formation. For instance, engine power, in effect the fuel flow (FF), is relatively high in the climb phase associated with a moderate time in mode. Hence, constraints enforced by the Air Traffic Management can cause inefficient operation to achieve reductions in noise levels. Regarding this, a comparison between the free speed departure procedure and the cost of noise increases was studied by Mitchell et al. and it is was found that there may be certain levels of CO_2 reduction at a cost of increasing noise exposure to below 70 db(A) at Gothenburg Landvetter Airport in Sweden. Although, the numerical level of noise exposure may be insufficient unless the noise foot print and the number of people exposed are not considered, the result indicates the necessity of a tradeoff between the two aspects of environmental impact, even ignoring economic parameters [11].

On the other hand, the fuel flow is quite high for a relatively higher time in mode for the cruise phase. As long as the range of the flight is sufficiently long and other conditions are considered constant, cruising closer to optimum cruise altitude provides a higher specific range, thereby lowering fuel consumption. However, there are certain other factors playing an important role in fuel consumption. Of these, wind effect on the fuel consumption of a flight is significant. In particular, for long range routes, with regard to the direction and speed of the wind, the total flight time can be drastically reduced (or increased). Therefore, in addition to optimum cruise altitude, consideration of existing wind speed and direction emerges as a useful technique for airlines in obtaining fuel savings. For instance, Rivas et al. report that by considering continuous tailwind (or headwind), an increase (or decrease) of 20 m/s in wind speed leads to a 700–1000 km increase (or decrease) in maximum range [14]. In this context, suitable wind conditions could not only suppress the benefits of cruising at optimum cruise altitude and yet yield significant fuel savings despite cruising at lower altitudes, but also promise reduced climate impact.

One important mitigating strategy concerning fuel consumption caused by delay, holding, or arrival traffic sequence, such as point merge with pre-defined legs or open STAR (standard arrival routes) downwind track, might be considered to be reduced cruise speed. Regarding lower cruising speeds, Prats and Hansen report that part of the delay could be absorbed in the air, thus providing a fuel saving of between 4 and 7%, compared to regular flight [13]. Net fuel savings can change mainly with range and also other performance parameters, while on the other hand, the success of this strategy depends heavily on sequent flights performed by aircraft having various performance. That is, lower performance aircraft followed by higher performance aircraft could lead to considerable fuel loss. Cavcar and Cavcar studied certain frequently used passenger aircraft in sequential cruise flight and calculated serious fuel loss when lower performance aircraft were followed by higher performance aircraft [3].

Defining the relationship between main flight parameters and fuel consumption can provide a better understanding of the environmental impact of cruise flight. For instance, in order to minimize contrail formation, which generates greenhouse gas affects, a solution involving a reduction of the cruising altitude emerges [8,10,15,18,19]. However, another trade off could arise as an increase in fuel consumption resulting from cruising at lower altitudes. In addition, the effects of other parameters of this trade off mostly remain unknown.

When the range of a flight is short, as seen in many domestic flights, also considering the mass of the aircraft, cruising several thousand ft below the possible higher altitude (below optimum cruise altitude) could provide benefits compared to the price to be paid climbing to possible higher altitudes. However, in order to measure the overall result, one should investigate not only the climb and cruise phases, but also the descent phase, since the distance from the top of descent (TOD) to the runway threshold can change due to the altitude of the TOD.

Lastly, despite a lower fuel flow, there may be large fuel saving opportunities during descent from an air traffic management perspective. For instance, the continuous descent approach (CDA) concept emerged to minimize low level flight, thereby reducing fuel consumption, and consequently emissions. However, although there have been numerous studies [4,5,17] demonstrating the concrete benefits, the success of the CDA depends heavily on air traffic volume.

From an emission perspective, to identify the impact of aviation on the atmosphere, there has been much research, mostly theoretical. These research studies generally aimed at investigating emissions resulting from aircraft activity in the vicinity of airports, calculating carbon footprints and suchlike. Most of these theoretical studies are based on the International Civil Aviation Organization (ICAO) emission database. This database publishes the emission performance of each new turbofan engine under certain circumstances, such as given engine power, time in mode and the fuel flow. Although being the most comprehensive investigation, there are certain drawbacks of the assumptions of this databank. For instance, emission tests have only been performed for the landing and takeoff (LTO) cycles with the cruise phase not included. Also, the fuel flow, and in turn the engine power, is always selected as a single value and emission production is based on this single value. However, it is well known that there are numerous parameters which have effects on fuel consumption. Therefore, considering constant fuel consumption rates may lead to incorrect emission production calculations. Additionally, only new engines are tested, leading to the emission performance of old engines remaining unknown.

Based on the information given above, the objectives of this study are to generate an empirical model explaining the cruise fuel flow based on the parameters of cruise altitude, speed and mass. The output of this study contributes to an understanding of the fuel consumption pattern of aircraft during the cruise phase. While defining this pattern, ICAO emission indices (or the results of other research), which are determined only for the LTO cycles, can be extended and implemented to cruise conditions. Therefore, the overall climate impact resulting from aviation could be evaluated better despite the existing drawbacks in the ICAO emission database mentioned above.

2. Data properties

In this study, actual flight data records are used. In this context, domestic flights performed by Turkish Airlines in January 2011 by 229 B737-700 (hereafter B737), 1712 B737-800 (hereafter B738), 228 A319, 1242 A320 and 686 A321 are investigated. All of the data was obtained from Turkish Airlines in a framework as part of a national project. Even though there are cruise flights at lower altitudes, due to their low frequency, the ones performed below 23,500 ft and 300 s are not considered, while the total data number ($N = 4097$) is obtained as higher than the total number of flights (3810) due to multiple cruises at different altitudes per flight. The number of routes is 31, the main departure and arrival base is selected as Istanbul Ataturk Airport and the flights are considered as round trips. The distances between the airports ranged from 178 nmi (International Istanbul Ataturk to International Izmir Adnan Menderes airports) to 686 nmi (International Istanbul Ataturk to Van Ferit Melen airports), while the mean distance is calculated as 413 nmi (SD = 147 nmi). Regarding ranges, according to a European Commission report in 2010, among the 48 city pairs where the highest traffics occur in Europe, 65% of total revenue passenger kilometers is obtained from routes below 700 nmi, based on the great circle distance [7]. In this regard,