

Research Article**Effect of Ambient Temperature Variations on the Direct Operating Cost of a Domestic Flight**Muhaned GILANI¹ , Durmuş Sinan KÖRPE² ¹ University of Turkish Aeronautical Association, Ankara, Turkey, mmgilani@thk.edu.tr , <https://orcid.org/0000-0002-9372-1477>² University of Turkish Aeronautical Association, Ankara, Turkey, dskorpe@thk.edu.tr , <https://orcid.org/0000-0002-7968-4999>**Article Info****Received:** May 23, 2019**Accepted:** July 4, 2019**Online:** July 12, 2019**Keywords:** Aircraft Fuel Consumption, Aircraft Performance Model, Temperature Variations, Airline Cost Index, Direct Operating Cost**Abstract**

This paper analyzes the direct effect of variable ambient temperature during the cruising phase and its effects on the strategies to reduce airlines direct operating costs. Fuel and time efficiency have become an increasingly important factor in the aviation industry. The fuel is one of the largest parts of airlines operating expenses and time is a parameter affecting direct operating cost items such as flight crew salaries, air traffic enroute charges and maintenance etc. A comprehensive aircraft performance model is developed to estimate the changes in fuel consumption and flight time by an Airbus 320-214 due to daily temperature variations. The seasonal change of the tropopause height is taken into the account in the atmosphere model. Cost index is kept as constant in the analyses. A domestic flight between Istanbul and Hakkari is used as a sample to predict changes in the direct cost of flight at day and night, in the summer and the winter seasons. The flight time is noticed to be changing significantly with respect to temperature variations.

To Cite This Article: M. Gilani, D. S. Korpe, "Effect of Ambient Temperature Variations on the Direct Operating Cost of a Domestic Flight" Journal of Aeronautics and Space Technologies, Vol. 12, No. 2, pp.197-207, Jul. 2019**Çevresel Sıcaklık Değişiminin Bir İç Hat Uçuşunun Doğrudan İşletme Maliyetine Etkisi****Makale Bilgisi****Geliş:** 23 Mayıs 2019**Kabul:** 4 Temmuz 2019**Yayın:** 12 Temmuz 2019**Anahtar Kelimeler:** Uçak Yakıt Tüketimi, Uçak Performans Modeli, Sıcaklık Değişimleri, Havayolu Maliyet Endeksi, Doğrudan İşletme Maliyeti**Öz**

Bu makalede, seyir uçuşu safhasında, değişken çevresel sıcaklığın havayolunun doğrudan işletme maliyetini düşüren stratejilerine etkileri incelenmiştir. Yakıtın ve zamanın verimli kullanımı, havacılık endüstrisinde gün geçtikçe daha da önemli bir faktör olmaktadır. Yakıt, havayolları işletme giderlerinin en büyük kalemidir. Zaman ise uçuş mürettebatı maaşları, hava trafiği yol ücretleri, bakım gibi doğrudan işletme maliyeti kalemlerini etkilemektedir. Airbus 320-214 tipi bir yolcu uçağının, yakıt tüketimindeki ve uçuş süresindeki değişikliklere, günlük sıcaklık değişiminin etkisini tahmin etmek için kapsamlı hava aracı performans modeli geliştirilmiştir. Tropoz yüksekliğinin mevsimsel değişimi de atmosfer modelinde hesaba katılmıştır. Analizlerde maliyet endeksi sabit tutulmuştur. Çalışmada, İstanbul ile Hakkâri arası iç hat uçuşu, kış ve yaz mevsimlerinde ve gündüz ve gece uçuşlarında doğrudan uçuş maliyetinin değişimi için incelenmiştir. Uçuş süresinin sıcaklık varyasyonu ile önemli şekilde değiştiği gözlenmiştir.

1. INTRODUCTION

The sector of air transportation has shown rapid growth and development over the past five decades. The accompanied development in aerospace technology has been magnificent, leading to a significant reduction in the costs of building and operating the airplanes, which motivated growing demand for air transportation services. In general, technology-based industries that

have rapid and continuous development in demand for their products or services have a large increase in their revenues. Contrary to this, the air transportation sector usually has a lower profit than the other sectors [1].

Reducing aircraft fuel consumption has become an increasingly important factor for airline companies. The main reason for that is the fuel which is the largest section of airlines operating costs. According to IATA,

this section is expected to be about \$180 billion in 2018 (accounting for about 23.5% of operating costs at \$73.0/barrel Brent). This is an increase of 20.5% over 2017 and is almost twice the \$91 billion fuel cost for 2005, which equivalent to 22% of operating costs at \$54.5/barrel Brent. In the year 2019, the fuel bill is expected to be \$200 billion, accounting for around 24.2% of operating costs at \$65/barrel Brent [2].

The main goal for market-oriented industries is to reduce the costs of production so that prices of their products can be reduced which is the only way for being comparative. So, reducing the total cost is related, but the effect of each individual element on the total cost relies on the directly related or unrelated factors. The sector of air transportation is categorized as a dynamic industry, with dynamic and fast changes in many of its structures. Because of this reason, decision-makers must have a wide perspective and a full understanding of the costs involved and the most efficient way to estimate them [3].

Considering Turkish Airlines, growth in the number of flights in the year 2017 was 10.4% in the domestic flights and 8.5% in the international flights and rate of increasing flights since the year 2013 was about 28% [4].

The aim of any airline is to operate efficient flights by reducing the costs of operations which is a subject of crucial importance to the operators. However, the costs are not only directly connected to the amount of fuel consumed for a specific flight, rather it is a function of the time of the operation. In general, the cost of the fuel is directly associated with the direct operating costs (DOC), which can be defined as all expenses associated with operating the airplane, it can be easily calculated based on fuel prices in the site of the operation. On the other hand, there are indirect operating costs (IOC), which includes other costs of operations other than the fuel costs, those are not considered as the operating costs of the aircraft itself, rather, they are classified in two different sections which are ground operating costs and system operating costs, such as, station and ground expenses - e.g., ground crew; and transport; handling fees paid to others, passenger services - e.g., flight crew salaries (could be DOC), and passenger insurance, ticketing, sales, advertisement, and administrative duties [5].

In civil aviation, the weather is considered as the major factor affecting aircraft operations, accounting for around 75% of the flight delays [6], and causing loses of hundreds of millions of dollars every year for the airlines' revenue [7]. So far, a few researchers have investigated the direct impact of changes in weather parameters such as ambient temperature on aircraft

operations [8]. This study will be the first of series of articles investigating the effect of changing weather and atmospheric parameters on the performance of the aircraft and on the direct operating cost of the airlines.

The atmospheric parameter in focus in this paper is the ambient temperature and its impact on the DOC. The temperature variations are expressed in the form of deviations from ISA, those deviations can be above or below the standard temperature which is +15°C. In general, those deviations have a direct effect on specific air range (SAR), true airspeed (TAS), and fuel flow (FF). TAS is directly proportional to Mach number and relative air temperature. When cruising at a constant Mach at a temperature higher than ISA true air speed will increase which leads to shorter flight time, hence saving time but with extra fuel consumption [9].

For an airline, the decision of which choice is better to be adopted, flying faster to save time, or slower to save fuel is a direct function of the cost index (CI), which is considered as a base of all performance calculations, mainly the optimum speed and the optimum altitude for the flight. [10], [11].

In order to help airline operators to predict the minor changes in aircraft performance due to variations in temperature, a precise aircraft performance model in requires, which will result in accurate estimation of the fuel and the time needed for the flight. Moreover, the model can help performance departments and policymakers to optimize the future schedule plans for their destinations based on the model outcomes.

It can be noticed from the literature that there is a lack of knowledge about the direct impact of temperature variation on the direct operating cost DOC of the flights. Many studies discuss this issue as a fuel-savings or fuel flow optimization, spearing this from the savings in flight time which is directly proportional to the direct operating cost.

Yanto and Liem [12] used the cruise-only approximation to simplify the analysis of fuel burn calculations, which is the same flight phase considered in this study. Dancila et al. [13] considered the factors responsible for the fuel consumption, and they are the wind, temperature, aircraft aging, gross weight, CG position, and altitude. However, it is not stated the direct impact of change in temperature on fuel consumption. Wickramasinghe et al. [14] explained the correlation between fuel consumption, flight time, and the cost index, considering the time constraints and optimum flight trajectories. Franco and Rivas [15] discussed the minimization of DOC at a constant altitude during the cruise phase, they found that the cost was minimal at specific CI and fuel consumption for given flight time.

The study also considers the effect of the wind on the DOC.

According to the literature review from the previous studies, it can be noticed that most of those studies discussed the optimization of flight trajectory for optimum fuel consumption, some others consider the effect of flight time on the DOC with or without considering the wind. However, deep investigation of the direct impact from the other weather conditions is not covered in details. This work aims mainly to develop a reliable tool by developing an algorithm to calculate the changes in aircraft performance and hence the DOC at all flight and atmospheric conditions as discussed in the following sections.

2. METHODOLOGY

2.1. Base of Aircraft Data (BADA)

One of nowadays methods for estimating aircraft performance is the mathematical modeling, the concept of the modeling in this study is built based on the approach of the Base of Aircraft Data (BADA), which is an Aircraft Performance Model (APM) designed by EUROCONTROL, via mutual cooperation with the manufacturers and operators of the air fleets. The BADA APM is developed for estimation of aircraft trajectories for the research and operations of Air Traffic Management (ATM).

The BADA APM consists of four sub-models: The action model computes the forces acting on the aircraft during flight (aerodynamic, propulsive and gravitational). The propulsion model provides an engine model to compute fuel consumption. Total Energy Model (TEM) which is the model that consider the geometrical, kinematic and kinetic characteristic of the aircraft motion is used to calculate aircraft performance and trajectory. Operations model provides information about the way the airline is operating the aircraft. The limitations model limits the aircraft actions to keep it within certain safety margin limits.

The corresponding mathematical models are expressed in the form of polynomial expressions [9],[10],[11].

2.2. Aircraft Performance Model APM

BADA consists of two main components which are the model specifications and the aircraft database. The specifications of the model describe the motion of the aircraft in flight by using basic aerodynamic, propulsive and gravitational equations. The aircraft database of BADA contains model coefficients for most of the aircraft types.

The APM of A320-214 equipped with CFM 56-5B4 is individually developed by writing an algorithm using Matlab programming language the model is developed based on the polynomial equations provided by BADA, those equations provide a general approach for modeling of a jet airliner which is the aircraft category used in this study [10], [11].

Airbus A320-214 general view is shown in Figure 1.

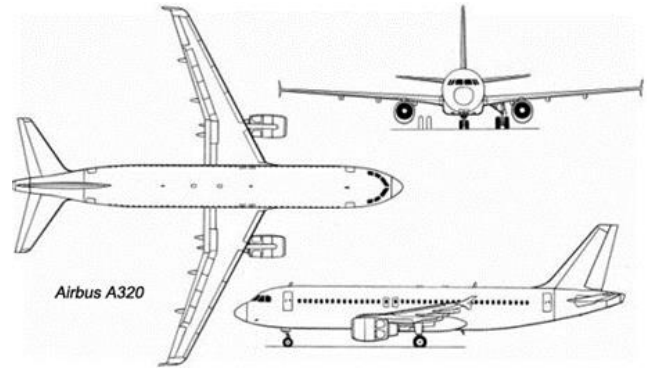


Figure 1. Airbus A320 general view [17].

APM implements both the empirical data from real flights and from BADA and the analytical data from the mathematical model of the aircraft. This model takes into consideration of all parameters affecting the performance of the aircraft such as the atmospheric conditions, aerodynamic characteristics, thrust, aircraft mass, wind, etc. The model can perform nonlinear simulation according to the initial inputs and continuous change in the mass due to fuel consumption during flight. APM diagram is shown in Figure 2.

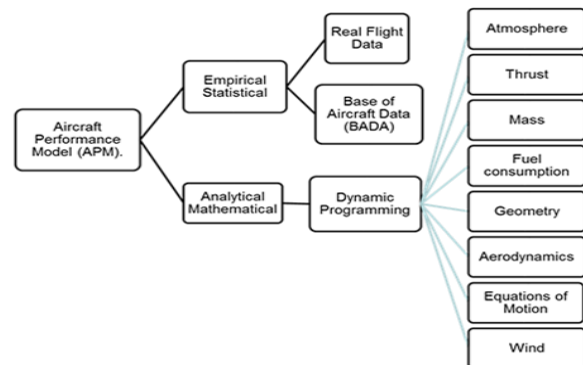


Figure 2. APM diagram.

The specifications of the aircraft are presented in Table 1 [17].

Table 1. Airbus A320-214 specifications [17].

Dimensions	
Length (m)	37.6
Wingspan (m)	34.1
Height (m)	11.8
Wing area (m ²)	122.4
Maximum take-off weight (kg)	78000
Maximum landing weight (kg)	66000
Operating empty weight (kg)	42600
Maximum zero fuel weight (kg)	62500
Maximum payload (kg)	16600
Performance	
Range with max payload (km)	6100
Cruise speed (km/h), (M)	840 , 0.78
Maximum speed (km/h), (M)	890 , 0.82
Maximum operating altitude (m)	11900
Engines	CFM 56-5B4
Thrust (KN)	2 x 111.2
Passengers capacity (1-class)	180

The model uses aircraft equations of motion based on Total Energy Model TEM concept. TEM equates the rate of increase in potential and kinetic energy to the rate of work done by forces acting on the aircraft, as shown in Equation (1)

$$(Th - D).TAS = mg_0 \left(\frac{dh}{dt} \right) + m.TAS \left(\frac{dTAS}{dt} \right) \quad (1)$$

where Th is the thrust force, D is the drag force, $\left(\frac{dh}{dt} \right)$ is the rate of climb, m is the mass of the aircraft, and TAS is the true airspeed.

The aerodynamic forces are the most significant forces affecting the aircraft flight, they are subjected to counties changes all along the flight path, those changes are mainly due to reduction in aircraft weight due to fuel consumption, change in speed and/or altitude, changes in atmospheric conditions and wind speed and direction, etc.

In this paper, the cruising phase is considered, at which the altitude is constant in this case the model is governed by the following equations, where lift is equal to weight and thrust is equal to drag:

$$L = W \quad (2)$$

$$Th = D \quad (3)$$

$$L = 0.5 . \delta . \gamma . P_0 . S . M^2 . C_L \quad (4)$$

$$D = 0.5 . \delta . \gamma . P_0 . S . M^2 . C_D \quad (5)$$

where L is the lift force, W is aircraft weight, D is the drag force, δ is the pressure ratio, γ is the Adiabatic index of air, P_0 is the pressure at sea level, S is the aircraft wing reference area, M is Mach number, C_L is the lift coefficient, and C_D is the drag coefficient.

At cruise phase the aerodynamic configuration considered as clean configuration where landing gear and high-lifting devices are not deployed.

As can be seen from Equations (6) and (7) Lift and drag equations are expressed as a function of Mach number M and pressure ratio δ [10], [11].

The lift coefficient C_L is obtained from Equation (6).

$$C_L = \frac{2.L}{\delta . \gamma . P_0 . S^2 . M . C_L} \quad (6)$$

BADA method specifies the drag coefficient, C_D , as a function of the lift coefficient C_L and the Mach number M . as shown in Equation (7).

$$C_D = \text{scalar} [C_0 + (C_2 + C_L^2) + (C_6 . C_L)] \quad (7)$$

The drag coefficient C_D is modelled as a polynomial of lift coefficient C_L , with coefficients depending on the Mach number M . Where, C_0 , C_2 and C_6 are coefficients provided by BADA according to available aircraft type and configuration.

The BADA is obtained from the Propulsive Forces Model (PFM), which depends on the type of engine, Turbo Fan Model (TFM), is the model used for A320. Each model includes the contribution from all engines and provides the thrust as a function of reference aircraft mass, atmospheric conditions and thrust coefficient C_T , which is the general formulation of the thrust force as expressed in Equation (8).

$$Th = \delta . W_{mref} . C_T \quad (8)$$

where W_{mref} is the reference weight of the aircraft, for Airbus A320 it is 77000 kg [17].

The thrust coefficient C_T is provided for this model based on cruise configuration as a function of Mach number, throttle parameter δ_T and thrust parameters a_n , which are given in the BADA database [10],[11], as shown in Equation (9).

$$C_T = f(a_{1-36}, \delta_T, M) \quad (9)$$

where

$$\delta_T = f(b_{1-36}, \delta, M) \quad (10)$$

where, a_{1-36} and b_{1-36} are the parameter sets that are given in the BADA database for a specific flight phase and aerodynamic configuration [10].

The algorithm calculates the fuel consumption as a rate of fuel flow per fraction of time, based on Equation (11), resulting from data inputs of the flight such as aircraft weight, altitude, true airspeed and atmospheric conditions including the effect of the wind.

$$FF = \delta \cdot \sqrt{\theta} \cdot W_{mref} \cdot a_0 \cdot L_{HV}^{-1} \cdot C_F \quad (11)$$

As it can be seen from the fuel flow FF equation, Equation (11), the fuel consumption is affected directly by the pressure ratio δ , speed of sound (a) and temperature ratio θ , which is varying with the recommended altitude and atmospheric conditions. It is also a function of fuel low heat value L_{HV} , which is the parameter of the fuel, and the fuel coefficient C_F which is provided as a function of Mach number, C_T and fuel coefficients f_n which are 25 parameters given in the BADA database as shown in Equation (12), the propulsive coefficients used for this code are those provided for CFM 56-5B4 turbo fan engine [9],[10],[11].

$$C_F = f(M, C_T, f_{1-25}) \quad (12)$$

The BADA coefficients provided in the previous equations are identified as non-linear coupled multivariate parameters. Instead of dealing with each engine type, aerodynamic configuration and thrust level setting as separate models, generalized models are introduced for aerodynamic drag, engine thrust and fuel consumption, that are valid for all cases.

2.3. Atmosphere Model

The atmosphere plays a major role in aircraft performance and in the operations. This model provides equations for the properties of the atmosphere, such as density, temperature, pressure, and speed of sound as a function of geopotential altitude, based on the International Standard Atmosphere (ISA). Those equations are required for calculation of aircraft performance, as well as calculations of CAS, TAS, and Mach number. The model of the atmosphere is expressed in Matlab by the equations governing the relations between atmospheric parameters such as pressure, temperature, density, tropopause height and their rate of change with changing altitude [10]. Also, the model can handle any temperature deviations from standard ISA. In the study, the wind is neglected.

2.4. Best Cruise Speeds and Cruise Altitudes

2.4.1. Maximum Range Cruise Speed (MRC)

The maximum range of a flight can be achieved by flying at a specific cruising altitude that gives maximum specific air range SAR. The speed of the aircraft at that yields the greatest SAR is known as the Maximum Range Cruise (MRC) speed. Flying at the MRC speed will minimize the fuel required to travel a specific cruise distance (in still air) [21], as shown in Figure 3 [21].

2.4.2. Long Range Cruise Speed (LRC)

The LRC speed is calculated by sacrificing a 1% from the maximum SAR and selecting the higher between MRC and LRC speeds [21], as shown in Figure 3 [24]. The LRC speed depends only on the performance characteristics of the aircraft, that is, without considering a specific costs related to a specific operator, LRC speeds are calculated and published in the Flight Crew Operating Manual (FCOM) of the aircraft by the manufacturer.

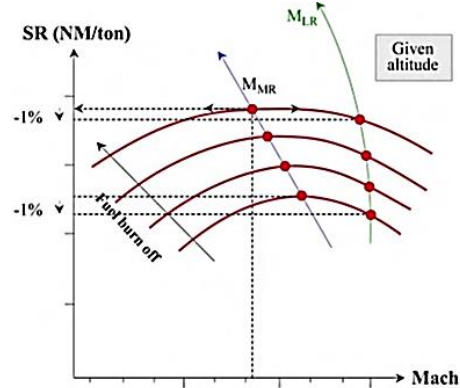


Figure 3. Maximum range cruise (MRC) and long range cruise (LRC) speeds (M) at different aircraft weights [24].

2.4.3. Economy Cruise Speed (ECON)

Practically, airlines choose to maintain a little higher speed than the MRC speed. The penalty for this faster speed is burning some extra amount of fuel, to gain some minutes from a shorter cruise time, as a result of flying that speed, the flight cost can be minimized. Time-related costs include all or part of the crew, maintenance, and operational costs can be reduced by flying shorter times by flying faster. The airlines aim to operate a flight at the lowest possible cost at a speed which is higher than MRC speed which will result in lowest fuel consumption, hence lower operating cost, that speed is called the Economy Cruise Speed (ECON).

ECON speed calculations are based on the individual cost structure, of the airline company, which is computed as a function of a cost index determined for the specific aircraft type and route [21], as illustrated in Figure 4. The DOC fraction of Figure 4 are obtained from the algorithm for a particular weight, altitude, temperature, and cost index.

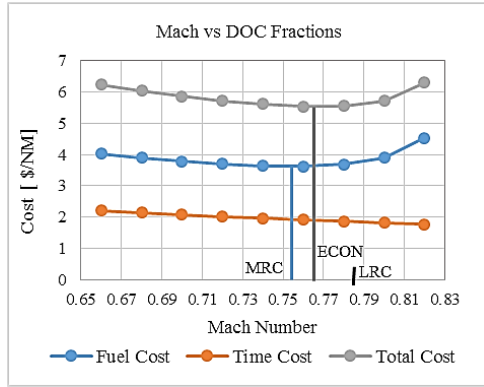


Figure 4. Characteristic Mach numbers for cruise according to cost fractions.

2.5. Cost Analysis

For a particular flight, the direct operating cost is expressed as the summation of fixed cost, fuel cost, and time-related costs, as shown in Figure 4. Time-related costs which can include all or part of the, maintenance, crew, and lease costs, can be minimized by cruising at a higher speed [21].

The cost management aims to minimize the total flight cost (C_t) (direct operating cost), this can be expressed mathematically in Equation (13) which is showing that, the total flight cost (C_t) comprises fixed costs (C_{fx}) and variable costs (C_v). Calculating C_v is the most challenging section in calculating and/or estimating total costs, Equation (14), shown the items included in calculating variable costs which is consist of cost of fuel CF multiplied by amount of fuel consumed (Δm), plus cost of time CT, which is expressed in the form of [\$/min] multiplied by the time (Δt) of the flight [10], [11].

$$C_t = C_{fx} + C_v \quad (13)$$

$$C_t = C_{fx} + CF \cdot \Delta m + CT \cdot \Delta t \quad (14)$$

Equation (14) can be rearranged as in Equation (15) to use a ratio between cost of time and cost of fuel (CT/CF).

$$C_t = C_{fx} + CF \cdot \left(\Delta m + \Delta t \cdot \frac{CT}{CF} \right) \quad (15)$$

As (C_{fx}) and CF do not change frequently, at least during a certain flight, the minimization of direct costs can be performed by the minimization of (CT/CF) ratio. That optimization must result in flying at optimum economy speed at optimum altitude, in other words conducting the flight with the minimum time and the minimum fuel consumption.

The ratio (CT/CF) is defined as the cost index, CI [kg/min], which is the ratio between time and fuel related costs [20], as expressed in Equation (16).

$$CI = \frac{CT}{CF} \quad (16)$$

2.6. Cost Index Cruise Management

The optimum cruise speed is the key factor in the management of the cost index, that speed is expressed as Mach number which is called Economic Mach number (MECON). MECON reduces the total cost CT of the cruising segment for a specific value of (CI), aircraft weight (W), cruise geopotential pressure altitude (H_p) and atmospheric conditions expressed as the ISA temperature deviation (ΔT).

The reduction of the total cost can be achieved by minimizing the Economy Cruise Cost Function (ECCF), which is expressed as a relation between cost index, fuel flow rate and ground speed (GS) of the aircraft [11]. As shown in Equation (17).

$$ECCF = \frac{CI + FF}{GS} \quad (17)$$

This function is optimized for obtaining the minimum value by using APM of Airbus 320-214 equipped with CFM 56-5B4 turbofan engine.

2.7. Model Validation

The mathematical model algorithm which is written in Matlab is validated from both statistical data provided by Eurocontrol aircraft database BADA4 and analytical data from the outputs of the code which is compared with collected data from real flights for the same type of aircraft at different flights and weather conditions in cruising phase. The results of the model from both approaches show an excellent match with results of BADA and FCOM.

As an example for the model validation the simulation is performed to compare the fuel consumption for a different aircraft weights at constant Mach number, M 0.78, ISA conditions, and cruising altitude of 35,000 ft (FL350), those flight parameters are chosen to be compared with published results from the FCOM of the same aircraft type [17]. As shown in Table 2, by

comparing the amount of fuel flow per one hour per one engine from FCOM and those obtained from the APM algorithm, it can be noticed that the maximum error is about 3% at light aircraft weights and it is about only 0.5% at heavy aircraft weights. Which is good enough to give an accurate estimation of fuel consumption at different flight and the weather conditions.

The APM algorithm accuracy improved by comparing its outcomes with the real flight data recorded in accordance with the recording inflight data procedure recommended by Airbus. These data were recorded during cruise phase at different flight condition including wind, aircraft weight, flight altitude, ambient temperature etc.

Table 2. Errors in calculated rate of fuel consumption at different aircraft weights from FCOM and APM [17], [19].

Weight [1000 kg]	Fuel Flow [kg/hr/Engine]		Error
	FCOM	APM	
54	1082	1049.752	3.07%
56	1098	1067.115	2.81%
58	1116	1086.965	2.60%
60	1135	1108.390	2.34%
62	1157	1131.570	2.20%
64	1180	1156.725	1.97%
66	1205	1184.125	1.73%
68	1235	1214.075	1.69%
70	1267	1246.940	1.58%
72	1301	1283.175	1.37%
74	1337	1323.310	1.02%
76	1374	1368.005	0.44%
78	1411	1418.065	0.50%

2.8. Flight Scenario

The flight scenario is a flight from Istanbul, Atatürk Airport (LTBA), to Hakkari, Yüksekova (LTCW). The total distance is 770 NM [21] according to the route used by Turkish Airlines, including 600 NM for cruising phase which is the phase considered in this study, the daily and seasonal average temperatures in both cities are shown in Table 3. The average daily and seasonal variations in ISA deviations along the route are shown in Table 4. [27].

Table 3. Daily and seasonal average temperatures at Istanbul and Hakkari.

Airport	Elevation (ft)	Summer Temp (C°)		Winter Temp (C°)	
		Day	Night	Day	Night
LTBA	163	+26	+16.5	+8.4	+3.1
LTCW	6096	+38.8	+24.9	-0.4	-8.0

Table 4. Average ISA deviations during the flight.

Enroute LTAB to LTCW	Summer Avr. ISA DEV (C°)		Winter Avr. ISA DEV (C°)	
	Day	Night	Day	Night
	+23.9	+11.9	-4.8	-11.3

The ISA deviations shown in Table 4 are used as a base of calculations for the daily changes in temperature, those values are used as an example for those deviations, any instantaneous values, if available, can be used as a real changes occur on daily basis. The other factor affecting temperature changes is the tropopause height which is subjected to change daily, seasonally and geographically. The height of troposphere is an essential input for flight performance calculations which is one of the basic inputs in the aircraft’s flight management computer FMC, pilots or dispatchers are usually use the significant weather charts SWC, which is valid for 24 hours, to find out what is the value of the instantaneous tropopause altitude along the route of the flight. At the tropopause the rate of decreasing temperature with increasing altitude will be zero, hence laps rate is zero at that layer, which will results in constant ambient temperature. An example of SWC is illustrated in Fig. 5 [26]. The average values were used for this route are 29,000 feet in the winter and 35,000 feet in the summer.

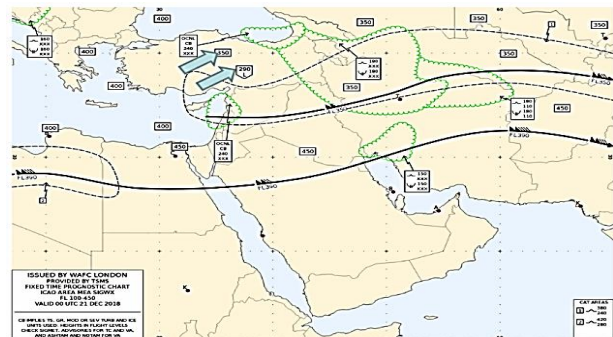


Figure 5. Weather sectional chart WSC.

The gross weight of the aircraft at the top of climb assumed to be 64 tons, the optimum altitude obtained from the APM is 37,000 ft and the cost index CI used is 15, which is the value recommended by Airbus for short and medium range routes [23], [24]. Airlines operating domestic flights in Turkey usually use cost index value between 15 and 20, which is estimated according to the airline estimation of its operating costs. By selecting 15 as a value for the cost index for this flight, the airline company declaring that, the cost of one minute of operation is equivalent to the cost of 15 kg of fuel, in other words, 1 minute of flying costs the company about 10.5\$, based on jet fuel price in December 2018 in Turkey, which is 0.7 \$. It can be seen clearly that, the optimization of flight parameters, hence, ECON and optimum altitude are directly affected by the cost index used, which is estimated by the commercial department of the company by considering direct and indirect costs.

3. RESULTS

The Results obtained from the algorithm are equivalent to FMC and FCOM of the aircraft, by selecting the suitable inputs based on the expected or actual flight scenario, as shown in Figure 6. The code computes the optimum altitude which is the altitude calculated from the largest value of SAR based on air craft weight and temperature, MECON which is the speed obtained from value of minimum ECCF, the air distance which is calculated from the navigation model of the code, (in this study only cruise distance is considered), the fuel required is calculated from the fuel consumption

function, and finally the time required for this cruise segment as a function of ground speed and travelled distance.

Inputs and outputs of the APM are shown in Figure 6.

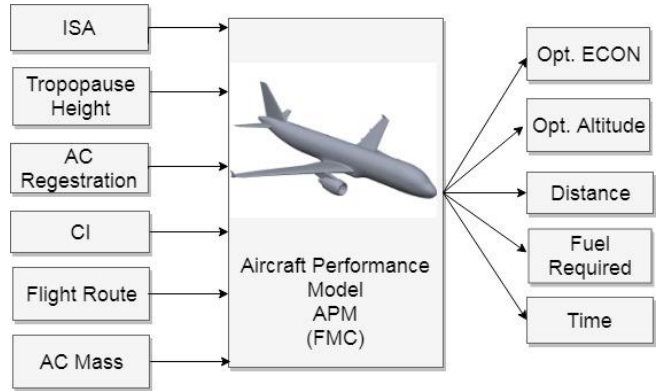


Figure 6. Inputs and outputs of APM.

The effect of ISA temperature deviations on the flight parameters such as speed of sound, air temperature and, air density are shown in Table 5. The pressure altitude shown in the table is the optimum altitude for this flight scenario. The tropopause altitude is considered based on average value in this region for both seasons, and as mentioned before it is obtained from the daily WSC reports.

Table 5. Effect of ISA temperature deviations on atmospheric parameters.

ISA DEV [C]	Pressure Altitude [ft]	Tropopause Altitude [ft]	Air Temperature [C]	Air Density [kg/m3]	Speed Of Sound [m/s]	Pressure [hPa]
23.9	37000	35000	-30.15	0.3137	312.50	218.84
11.9	37000	35000	-42.15	0.3286	304.69	217.87
0	37000	36000	-56.330	0.348	295.19	216.64
-4.8	37000	29000	-47.26	0.3385	301.30	217.75
-11.3	37000	29000	-53.46	0.3420	297.14	215.49

The effect of ISA temperature deviations on the direct operating cost of the flight can be expressed in terms of fuel saving in kilograms and time savings in minutes. For more comprehensive results the simulation is conducted for the daily changes in the summer and in the winter separately, as illustrated in Table 6.

Table 6. Cruise performance results in summer time.

Summer	MECON	ISA DEV [C°]	Time [min]	Fuel [kg]
Day	0.7655	+23.9	77.42	2982.9
Night	0.7667	+11.9	79.27	2984.1
		Δ	+1.85	+1.2
Total Δ cost = + 20.265 \$				

In the case of summer season, operating the flight at nighttime instead of the daytime, as seen in Table 6, will add 1.85 min to the flight time, and 1.2 kg of fuel even though the speed used is the economy speed ECON, which is calculated for every case separately, in total this will add 20.265 \$ to the flight direct operating cost. In the case of winter season, as shown in Table 7, conducting the flight at nighttime where temperatures are lower, the flight time will be longer by 2.05 min and saving 4.0 kg of fuel, this will result in a total extra cost of 18.725 \$. As shown in Table 7.

Table 7. Cruise Performance Results in Winter Time.

Winter	MECON	ISA [C]	Time [min]	Fuel [kg]
Day	0.7635	-4.8	80.50	2978.7
Night	0.7657	-11	82.55	2974.7
		Δ	+2.05	-4.0
Total Δ cost = + 18.725 \$				

It can be noticed from the results that, the effect of temperature variation on fuel consumption is very small due to flying at the optimum MECON at flight different conditions. However, the effect of changes of TAS plays the major role in changing the flight time for each case.

The algorithm calculates the total direct operating cost from calculated cost of time and cost of fuel. According to this study case, the time cost is the dominant fraction of DOC, as it can be seen from Table 8, the total direct operating cost is calculated, showing clearly that the most affected fraction is the cost of time CT, while the cost of fuel CF is almost constant.

Table 8. Results of total direct operating costs.

Season / Time		Time [min]	CT [\$]	CF [\$]	Total Cost [\$]
Summer	Day	77.42	812.89	2088.1	2900.99
	Night	79.27	832.37	2088.8	2921.17
Winter	Day	80.50	845.32	2085.10	2930.42
	Night	82.55	866.77	2082.36	2949.13

For more clarification the differences in the cost of time CT at different daily and seasonally temperature variations are illustrated separately in Fig.7.

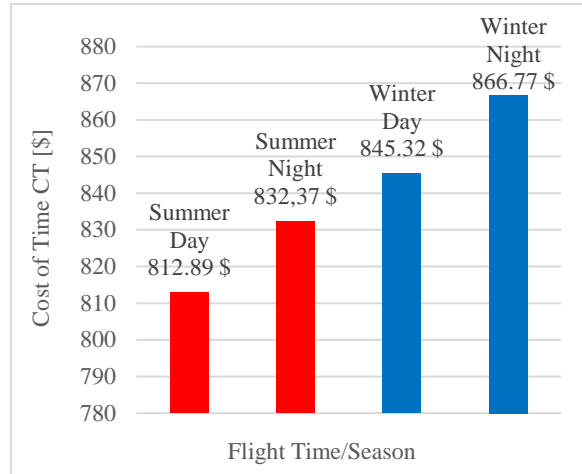


Figure 7. Cost of Time for different temperatures.

4. CONCLUSIONS

In general, estimations of flight cost is a complex process subjected to many parameters and variables. The most difficult factors to be estimated are those time-dependent factors which must be handled with great care and on daily and route bases.

This paper discusses the effect of one of the atmospheric dynamic parameters that play a major role in the airlines estimations of optimum flight performance and its impact on strategic planning of flight scheduling and fleet management.

It can be observed from the results that, there is a significant effect of the temperature variations on aircraft cruise performance and consequently on the direct operating costs of the flight. The main effect of temperature is on fuel consumption, calculations of the optimum speed, and the optimum altitude to be maintained. The other factor which is affected by the temperature is the endurance of the flight because of the direct effect of the temperature on the TAS at a constant Mach number, temperature deviation above ISA leads to higher TAS and consequently shorter flight time, and vice versa, in the case of temperatures lower than ISA.

From the flight scenario, it can be noticed that, the effect of selecting the best time interval to operate the flight will have a direct effect on the DOC. In the summer season, for instance, flying during the daytime at highest average temperature will save about 20\$ per flight (one landing), than if the flight performed at night. Assuming that an airline operating two daily flights on this route (four landings), this will be about 29,000 \$ of savings per year.

In conclusion, the savings in this study case are in the cost of time not in the cost of fuel, however this is directly affected by the cost index chosen by the airline.

Finally, this paper aims to shed some light on the effect of temperature variations of technical and economic performance of a flight. The results show significant variations on the direct operating costs, those can be used for better understating of the effect one of the atmospheric parameters on strategic flight planning for operating more efficient and optimum flights.

5. REFERENCES

- [1] R. Doganis, "Flying off Course: Airline Economics and Marketing," Fourth Edition. Routledge, London, 2010.
- [2] International Air Transport Association (IATA), "FACT SHEET: Fuel," Dec-2018. [Online]. https://www.iata.org/pressroom/facts_figures/fact_sheets/Documents/fact-sheet-fuel.pdf [Accessed: Dec. 15, 2018].
- [3] R.A.G. Eller and M. Moreira, "The Main Cost-Related Factors in Airlines Management." *Journal of Transport Literature*, Vol. 8, No. 1, pp. 8-23, 2014.
- [4] Turkish Airlines THY, Annual report, 2017, [Online], http://investor.turkishairlines.com/documents/ThyInvestorRelations/eng-thy_cift.pdf [Accessed: Dec. 21, 2018].
- [5] P. Belobaba, A. Odoni, and C. Barnhart (Eds.), "Airline Operating Costs and Measures of Productivity in the Global Airline Industry," 2nd ed., *John Wiley & Sons*, Chichester, UK, 2016.
- [6] J. M. Rosenberger and Coauthors, "A Stochastic Model of Airline Operations," *Transp. Sci.*, Vol. 36, pp. 357–377.
- [7] S. Lan, J. P. Clarke and C. Barnhart, "Planning for Robust Airline Operations: Optimizing Aircraft Routings and Flight Departure Times to Minimize Passenger Disruptions," *Transp.*, 2006.
- [8] P. D. Williams, and M. M. Joshi, "Intensification of Winter Transatlantic Aviation Turbulence in Response to Climate Change." *Nat. Climate Change*, Vol.3, pp.644–648, 2013.
- [9] L. Delgado and X. Prats, "Fuel Consumption Assessment for Speed Variation Concepts During the Cruise Phase" *Conference on Air Traffic Management (ATM) Economics*, Belgrade, 2009.
- [10] EUROCONTROL. Base of Aircraft Data (BADA), http://www.eurocontrol.int/services/bada_. [Online] [Accessed: Jan. 2019].
- [11] EUROCONTROL. "User Manual for the Base of Aircraft Data (BADA) Revision 4.1." User Manual, 2016.
- [12] J. Yanto, and R. P. Liem, "Aircraft Fuel Burn Performance Study: A Data-Enhanced Modeling Approach" *Transportation Research Part D: Transport and Environment*, Vol. 65, pp. 574-595, 2018.
- [13] B. Dancila, R. M. Botez and D. Labour, "Fuel Burn Prediction Algorithm for Cruise, Constant Speed and Level Flight Segments," *The Aeronautical Journal*, Vol. 117, No. 1191, 2013.
- [14] N. K. Wickramasinghe, Y. Miyamoto, A. Harada and Y. Fukuda, "Flight Trajectory Optimization for Operational Performance Analysis of Jet Passenger Aircraft," *Transactions of the Japan Society for Aeronautical and Space Sciences, Aerospace Technology Japan 12 (APISAT-2013): a17-a25*, 2014.
- [15] A. Franco and D. Rivas, "Minimum-Cost Cruise at Constant Altitude of Commercial Aircraft Including Wind Effects" *Journal of Guidance Control and Dynamics*, Vol. 34, No .4, pp. 1253-1260, 2011.
- [16] EUROCONTROL EXPERIMENTAL CENTRE, Concept Document for the Base of Aircraft Data (BADA) Family 4, 2012.
- [17] Airbus A318/A319/A320/A321 FLIGHT CREW OPERATING MANUAL FCOM, 2005
- [18] Airbus, Getting to Grips with Fuel Economy, Blagnac, France, Jan. 2004.
- [19] Airbus, Getting to Grips with Aircraft Performance monitoring, Blagnac, France, Jan. 2002.
- [20] Airbus, Getting to Grips with the Cost Index, Blagnac, France, Jan. 1998.

- [21] Trevor M. Young, "Performance of the Jet Transport Airplane Analysis Methods, Flight Operations, and Regulations," *Wiley*, 2018.
- [22] W. Roberson, R. Root and D. Adams, "Fuel Conservation Strategies: Cruise Flight," *Aero*, The Boeing Company, Seattle, WA, Vol. 4, pp. 23–27, 2007.
- [23] L. Seto, "Cost Index," *Flight Operations Engineering*, Boeing Commercial Airplanes, Seattle, WA, 2009.
- [24] Airbus, "Getting to Grips with Aircraft Performance," Flight Operations Support and Line Assistance, Airbus S.A.S., Blagnac, France, Jan. 2002.
- [25] Sky Vector Aeronautical Charts, <https://skyvector.com/>, 2018.
- [26] Tarım ve Orman Bakanlığı Meteoroloji Genel Müdürlüğü. <https://mgm.gov.tr/>, 2019.
- [27] The Turkish State Meteorological Service, <https://hezarfen.mgm.gov.tr>, 2019.

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