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# ANALYSIS OF INFLUENCE OF CRUISE SPEED AND FLIGHT LEVEL CHANGE ON FUEL CONSUMPTION IN AIR TRAFFIC FLOW MANAGEMENT

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***Abstract*****—***The problem of flight planning in case of delay demands is considered. The criterion restrictions between fuel consumption and the required flight time when the nominal cruise speed changes are investigated. It is proved that flight delay in the air can be realized without additional fuel costs, which is determined and estimated in the absence or presence of wind. The impact of choosing a different flight level and using additional fuel to obtain a longer delay was also considered and analyzed. The results show that for different flight levels and wind direction the delay may be varied from 3 minutes to 13 minutes. The initial flight level is defined as one of the main parameters that affect the amount of delay in the air.*

**Index Terms—**Ground delay program; airborne delay; equivalent cruise speed; air traffic flow management; required arrival time.

## I. INTRODUCTION

The growth of aviation and the urgent need to reduce fuel consumption and emissions demand increased airspace and airport capacity. Today, most air transport infrastructures suffer from delays in departures and arrivals. This situation is exacerbated by the constant traffic increase and due to the shortcomings of landing and take-off schemes at airports due to regional factors. The weather is also one of the main reasons that leads to a decrease in the accuracy of flights. To mitigate these imbalances, air traffic flow management (ATFM) initiatives are being implemented, in which departure delay is considered as a major factor. The increase of flights' intensity leads to an increase of dangerous (or potentially dangerous) situations occurrence likelihood. With the knowledge of delay at the departure airport, one can predict the arrival schedules, which are already determined in the congested infrastructure. However, predicting delays is usually a difficult task. This leads to unnecessary lengthy regulatory activities and, consequently, to unnecessary delays and underutilization of infrastructure capacity.

## II. PROBLEM STATEMENT

The aircraft is associated with four-dimensional trajectory (latitude, longitude, altitude and time) according to trajectory-based operations (TBO) paradigm [1].

Any changes are continuously considered and solved by local authorities with respect to legacy flight plans. These initiatives are intended to improve considerably the scheduling performance as a part of ATFM system from its current largely centralized and tactical nature to more strategic and distributed paradigm.

Ground Delay Program (GDP) is one of ATFM initiative [2] to introduce the intended delay in flights in case when the capacity of destination airport is not enough for arrival demands. Another variant is the airborne traffic delay [3] to avoid the expensive ground stops and maintenance costs.

One more widely used approach to the scheduling performance improve is based on the introduction of Performance Based Navigation (PBN) concept that has been developed and introduced by the International Civil Aviation Organization (ICAO). It represents a shift from traditional sensor-based navigation (using ground-based beacons) to Area Navigation (RNAV) and Global Navigation Satellite Systems (GNSS) use [4]. The accuracy and continuity of GNSS-based services may be significantly improved by Ranging Integrity Monitoring Station (RIMS) installation in the appropriate region to extend the coverage of European Geostationary Navigation Overlay Service (EGNOS) service [5].

Four-dimensional trajectory (both lateral and vertical) must be calculated within the flight plan constraints and aircraft performance limitations, based on entered atmospheric data and the crew-selected modes of operation.

The lateral path and predicted fuel, time, distance, altitude, and speed are obtained for each waypoint.

The main parameter to calculate is ground speed. The speed schedules are typically constant for climb and descent phases, and the true airspeed (TAS) increases with altitude for the constant Mach number and decreases with low altitude.

For further considerations let's use the model of aircraft flight as following assuming the aircraft as material point:

$$\mathbf{X} = \begin{bmatrix} x & y & h & V & \psi & m \end{bmatrix}^{\mathrm{T}}, \qquad (1)$$

where state vector **X** contains the coordinates of aircraft $x$, $y$ in horizontal plane (in local great circle coordinate system), the aircraft altitude $h$, true airspeed $V$, aircraft course $\psi$ and mass $m$.

In dynamics the equation (1) can be determined via additional parameters:

$$\dot{\mathbf{X}} = \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{h} \\ \dot{V} \\ \dot{\psi} \\ \dot{m} \end{bmatrix} = \begin{bmatrix} V\cos\psi\cos\Theta + w_x \\ V\sin\psi\cos\Theta + w_y \\ V\sin\Theta + w_h \\ \dfrac{T-D}{m} - g_0\sin\Theta \\ \dfrac{L\sin\gamma}{mV} \\ -\eta T \end{bmatrix}, \qquad (2)$$

which are the following: $\Theta$ is the trajectory inclination angle; $g_0$ is the acceleration of gravity force at mean sea level (MSL); $\gamma$ is the bank angle; $\eta$ is the specific fuel consumption by thrust; $T$ is the thrust force, $D$ is drag force; $L$ is aerodynamic lift force; $w_x$, $w_y$, $w_h$ are components of wind velocity.

Drag and lift forces in (2) can be determined in terms of TAS as following:

$$L = \frac{C_L S\rho}{2}V^2, \qquad D = \frac{C_D S\rho}{2}V^2, \qquad (3)$$

where $C_L$ and $C_D$ are correspondingly the lift and drag coefficients; $S$ is the lifting area of wing; $\rho$ is the air density.

Coefficients and critical values for parameters in model (3) and 4 are usually taken from aircraft performance data base known as BADA – Base of Aircraft Data [6] created by EUROCONTROL and provided to users with license.

The problem statement is formulated as finding the possible change in cruise speed (expressed in Mach number) for controlled airborne delay ($t_{\text{delay}}$) and its influence of fuel consumption $\eta$ taking into account the possible variation in wind and flight level (FL).

## III. REVIEW OF EXISTING APPROACHES

Airborne delay is considered in [3]. Authors provide investigations of wind influence on airborne delay and fuel consumption on the case study of Chicago airport. They use so called equivalent cruise speed and allow minimal safe value for airborne and ground delays under the constant conditions.

Another variant is presented in [7]. Here the airborne delay is reached by strategy of linear holding, but again it is based on reduction of cruise speed to minimal limit.

But in most of the cases it is necessary to take into account the altitude and speed margins for flight safety, and therefore the influence of atmospheric changes is unavoidable.

Let's use the model proposed by [8]. Mach number can be calculated as following:

$$\mathrm{M} = \sqrt{\left(\frac{1}{\delta}\left\{\left(1+0.2\left(\frac{\mathrm{CAS}}{661.5}\right)^2\right)^{3.5} - 1\right\} + 1\right)^{0.286} - 1}, \qquad (4)$$

where CAS is calibrated airspeed (usually in knots), $\delta$ is atmospheric pressure ratio (actual pressure / standard pressure).

True airspeed is connected with CAS and M number in (4) as following:

$$\mathrm{TAS} = 661.5\mathrm{M}\sqrt{\theta}, \qquad (5)$$

where $\theta$ is atmospheric temperature ratio (actual temperature / standard temperature).

The model of fuel consumption is proposed in [9] based on database BADA. The fuel burn rate (kg/min) as function of TAS is the following:

$$f(V) = c_1V^3 + c_2V^2 + \frac{c_3}{V} + \frac{c_4}{V^2}, \qquad (6)$$

where coefficients $c_1$, $c_2$, $c_3$, $c_4$ are taken for each type of aircraft [6] in terms of its aerodynamic forces (3).

## IV. EXPERIMENT DESCRIPTION

Simulation was performed in JEPPESEN FliteStar 9.5.5.0 environment for the Boeing 737-300 aircraft for the typical European flight: UKBB Boryspil' (N 50° 20.2', E 30° 54.3') – LFPB Le Bourget (N 48° 58.1', E 02° 26.4'). The distance for a selected route according to Instrument Flight Rules (IFR) was 1417 NM.

Variable parameters in a system were:

- cruise flight speed;
- flight level;
- wind settings.

Cruise speed was set in terms of M number, in a range from 0.74 M to 0.78 M. Wind speed was varied from 30 to 50 kts, and direction was selected as tailwind and headwind.

For the simulation of atmospheric disturbance, the model of standard atmosphere was used in (4) and (5). The parameters of standard atmosphere are given at MSL: temperature $T_0 = 288°K$, pressure $p_0 = 101325$ Pa, density of air $\rho_0 = 1.225$ kg/m$^3$, and speed of sound $a = 340$ m/s.

The meteorological data for simulation was taken from internet resource [10].

## V. OBTAINED RESULTS

In the result of parameters' variation, a finite number of simulated navigation logs was obtained with the output parameters of flight time, used fuel, speed, altitude, followed waypoints, etc.

Figure 1 demonstrates the dependence of fuel consumption in kg on the selected cruise Mach speed. The number of speed points was limited to three due to lack of knowledge of technical characteristics of aircraft in the intermediate points. It appears that the lowest fuel consumption (6549 kg) can be obtained at the lower acceptable values of cruise speed (0.74 M in our case) and at the highest possible FL (370 in our case). Correspondently we get the highest fuel consumption (7746 kg) at highest acceptable cruise speed (0.78 M) at lowest FL310.

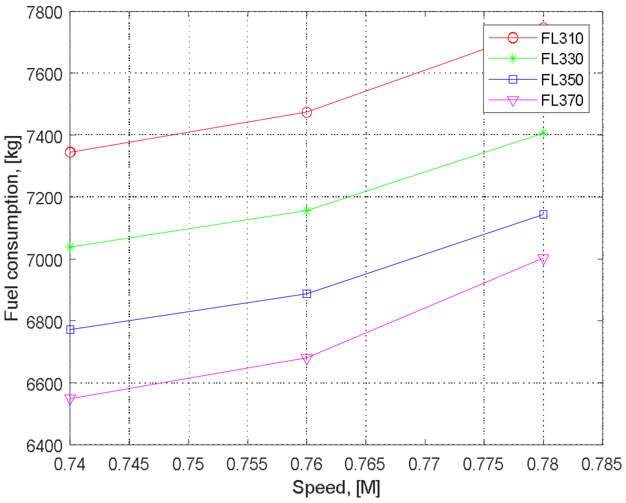

Fig. 1. Dependence of fuel consumption on cruise speed at various flight levels

Figure 2 demonstrated the dependence of flight duration on the cruise speed. As it can be seen from the figure, the lowest flight duration was 194 min (at cruise speed 0.78 M, and FL310), and the highest was 207 min (at cruise speed 0.74 M, and FL370).

The dependence of fuel consumption on the flight duration with variable cruise speeds and FLs is presented at the Fig. 3.

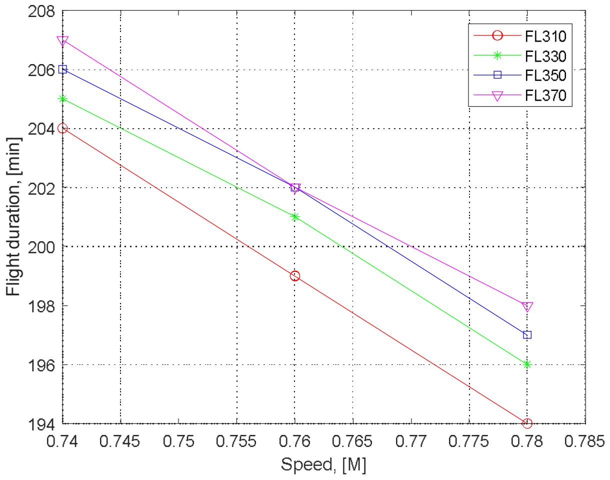

Fig. 2. Dependence of flight duration on cruise speed at various flight levels

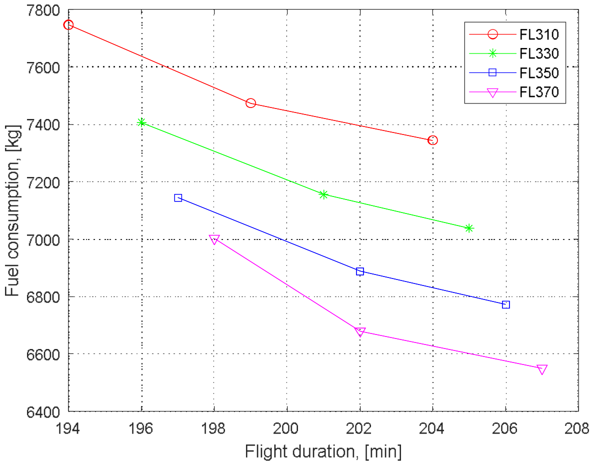

Fig. 3. Dependence of fuel consumption on flight duration at various flight levels

Results of simulations with wind presence for FL350 are presented in Table I. As it might be seen, two wind directions were tested as the ones having the most significant influence on results, the headwind and tailwind. It appeared that the headwind with speed of 50 kts may save the fuel on approximately 8 % and reduce time of flight on 15 minutes. At the same time, the same value of wind speed in the inverse direction (tailwind) may increase flight time on 20 minutes and increase fuel consumption on almost 10%.

TABLE I RESULTS OF SIMULATIONS WITH WIND PRESENCE FOR FL350

| **Wind direction, [deg]** | **headwind** | **headwind** | **headwind** | **0** | **tailwind** | **tailwind** | **tailwind** |
|---|---|---|---|---|---|---|---|
| **Wind speed, [kts]** | 30 | 40 | 50 | **0** | 30 | 40 | 50 |
| **Total time, [h]** | 03:17 | 03:14 | 03:11 | **03:26** | 03:37 | 03:42 | 03:46 |
| **Total fuel, [Lbs]** | 14216 | 14005 | 13783 | **14929** | 15743 | 16048 | 16370 |

## VI. CONCLUSIONS

The results show that for different flight levels and wind direction the delay may be varied from 3 minutes to 13 minutes. The initial flight level is defined as one of the main parameters that affect the amount of delay in the airborne delay, but here the cost index and flight safety considerations (including the limitation on minimal stalling speed) have not been taken into account.

Also, one of important factor is the weather, namely wind. The maximal variation in flight time is 29 minutes under the same other conditions.

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**М. П. Мухіна, С. І. Ільницька. Аналіз впливу зміни крейсерської швидкості та ешелону польоту на споживання палива в керуванні повітряним потоком**

Розглянуто проблему планування польоту на випадок затримки. Досліджуються критеріальні обмеження між витратою палива та необхідним часом польоту при зміні номінальної крейсерської швидкості. Доведено, що затримка польоту в повітрі може бути реалізована без додаткових витрат на паливо, що визначається та оцінюється за відсутності або присутності вітру. Також було розглянуто та проаналізовано вплив вибору іншого рівня польоту та використання додаткового палива для отримання більшої затримки. Результати показують, що для різних рівнів польоту та напрямку вітру затримка може варіюватися від 3 до 13 хвилин.

Початковий рівень польоту визначається як один з основних параметрів, що впливає на величину затримки в повітрі.

**Ключові слова**: програма наземної затримки; бортова затримка; еквівалентна крейсерська швидкість; керування потоком повітряного руху; необхідний час прибуття.

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**М. П. Мухина, С. И. Ильницкая. Анализ влияния изменения крейсерской скорости и эшелона полета на потребление топлива в управлении воздушным потоком**

Рассмотрена проблема планирования полетов при запросах на опоздание. Критерийные ограничения между расходом топлива и требуемым временем полета при изменении номинальной крейсерской скорости исследуются. Доказано, что задержка полета в воздухе может быть реализована без дополнительных затрат на топливо, которые определяются и оцениваются при отсутствии или наличии ветра. Также было рассмотрено и проанализировано влияние выбора другого эшелона полета и использования дополнительного топлива для увеличения задержки. Результаты показывают, что для разных эшелонов полета и направления ветра задержка может составлять от 3 до 13 минут. Начальный эшелон полета определяется как один из основных параметров, влияющих на величину задержки в воздухе.

**Ключевые слова**: программа наземной задержки; задержка в воздухе; эквивалентная крейсерская скорость; управление потоками воздушного движения; требуемое время прибытия.

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