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AIRCRAFT FUEL CONSUMPTION AND EMISSIONS DURING CRUISE, EFFECT OF THE JET STREAM

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Abstract

Article presents the results of fuel consumption calculation during cruise compared to remaining aircraft flight phases. Based on fuel consumption, methodology of pollutants quantitative estimation emitted by turbine engines has been developed. Material provides evaluation results of aircraft CO_2, CO and NO_x effusion using fuel consumption data taken from aircraft Flight Data Recorder (FDR) during cruise of various aircraft types.

Knowledge of the amount of aircraft emissions on high altitudes is very important for climatologists in order to understand eventual changes in the Earth atmosphere due to aviation activities.

The authors would like to draw attention of the aviation professionals to the fact that aircraft fuel consumption during cruise; thereby amount of toxic content in the exhaust from the turbine engine is significantly higher especially during flights against jet stream.

Thousands flights of two operators were processed using algorithms developed by authors.

The article gives an example of fuel consumption and thereby CO_2, CO and NO_x emission estimation based on engine performance taken from their test cell results. Calculations were performed with the consideration of the factor for engines deterioration through operation time provided by its manufacturer.

Keywords: *turbine engine, cruise, jet stream, exhaust emissions*

1. Introduction

Aviation produces only less than three percent of total mankind emissions, but most of greenhouse and toxic gases are dispersed at high altitudes. Therefore, negative impact on environment probably is much higher than that seen from such fractional share.

B767 with its two engines installed, on North Atlantic, route flight (approx. 9.5 hour) emits around 150 tons of CO_2 and 450 kg of NO_x. How many flights daily, only between Europe and North America are operated by airlines? 1000? Many of them are performed by aircraft like B747 or A340 equipped with four engines and emit more poisonous gases than twin engines aircraft. All these mass of pollutants aviation is dispersing at approx. 10000 m.

Around aviation, due to its significant visibility, especially emissions produced by this mean of transport, there is the atmosphere of exaggeration in the assessment of its impact on the environment. Knowledge about aircraft quantitative emissions is important in order to assess real influence on ionosphere. We engineers have to provide scientists – Earth atmosphere experts, information concerning quantitative part of pollutants contained in the engine exhaust.

It should be emphasized that in aviation there are no standards for emissions of carbon dioxide, or even any emissions out of landing and take-off cycle (detailed information could be found in [5] and [8]).

This paper describes developed in the Institute of Aviation concept of CO, NO_x and CO_2 emissions estimation by aircraft on high altitudes. Algorithm precisely defining various aircraft flight phases has been introduces. There were more than 7000 flights of different aircraft analysed and 40 engines test – cell performances were examined in order to determine equations of the exhaust emissions. As a result it can be stated that estimated quantitative aircraft emission of basic pollutants (NO_x and CO) and CO_2 contained in the jet engine exhaust on high altitudes can be provided for any operator, which has QAR (Quick Access Recorder) on the aircraft board installed. Examples are given for four types of the aircraft.

2. Engines test – cell performances

Each jet engine regardless of whether it is new or overhauled has different performances.

They are shown in the engine data submittal – of new or in the test – cell report of overhauled engines. The difficulty and complications lie in the fact that each engine of the same type, installed on the same type of the airframe has different characteristics, so for each aircraft it is necessary to determine its engine performances. Than during exploitation tracking every engine individually its critical parameters changes.

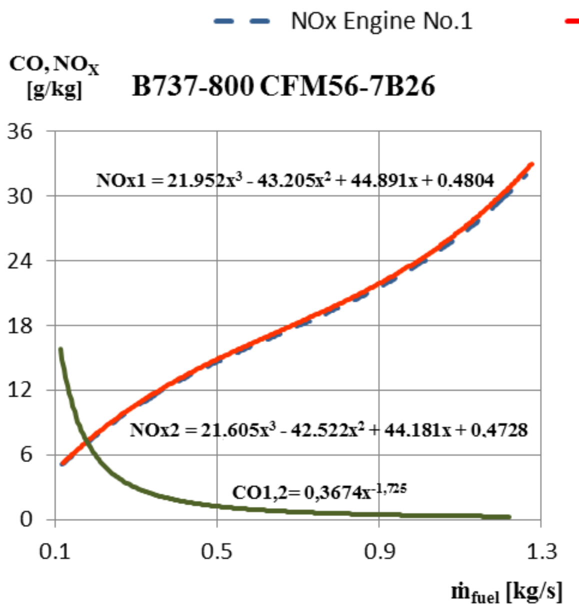

Fig. 1. Dependence of NO_x emission from fuel consumption of the engines installed on B737-800

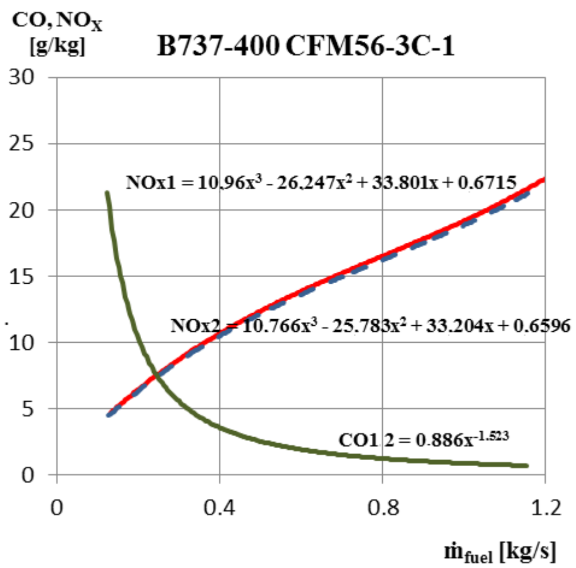

Fig. 2. Dependence of NO_x emission from fuel consumption of the engines installed on B737-400

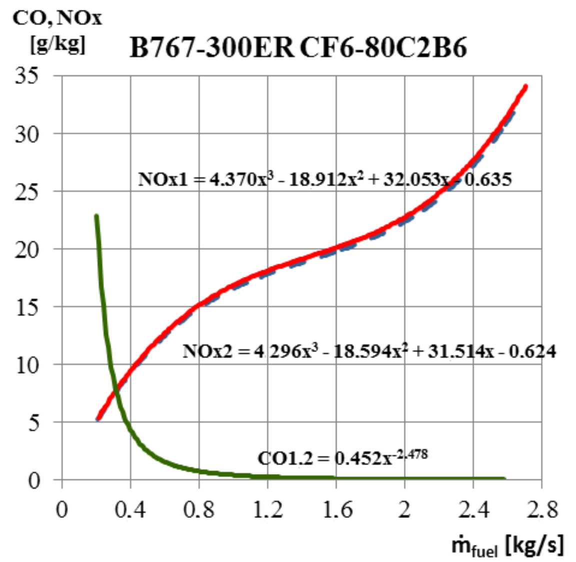

Fig. 3. Dependence of NO_x emission from fuel consumption of the engines installed on B767-300ER

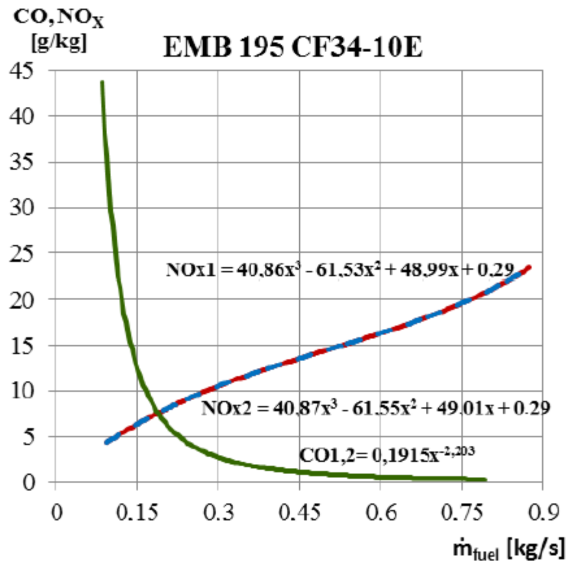

Fig. 4. Dependence of NO_x emission from fuel consumption of the engines installed on ERJ 195

Knowing fuel consumption values it is easy to determine NO_x emissions for any type of particular aircraft. They are always described by polynomial of the third degree. Emissions of CO for engines installed on different types of aircraft are determined based on methodology presented in [5] and [9]; it is why CO values are the same for every engine installed on same type of aircraft. Figs. 1-4 are showing for each engine installed on the aircraft NO_x emissions and their equations depending on fuel consumption. CO emission equations are given for reference.

Having so determined mathematical formulas describing emissions and knowing real fuel consumption and duration of individual flight phases taken from QAR it can be counted quantitative emissions value during flight specific manoeuvres. Fig. 5 and 6 are presenting results of emission calculations for specific B767-300ER, the same as for previous example (Fig. 3). Remaining aircraft types are not showed and only calculations results are presented below:

For the long haul destinations „share" of the cruise part is almost 86% of total duration of the flight, when for European connections is only 60%. For example, B767-300ER leaves on 10000 m altitude, approx. 475 kg of NO_x during flight from Europe to US (2 kg_{NOx}/passenger), whilst ERJ 195 emits on same altitude 35 kg of NO_x (0.37 kg_{NOx}/passenger). It is also worth noting that take-off cycle, only phase of flight described by emissions regulations, depending on destination takes from 5% (long haul flight) to 15% (short flight) of total flight duration.

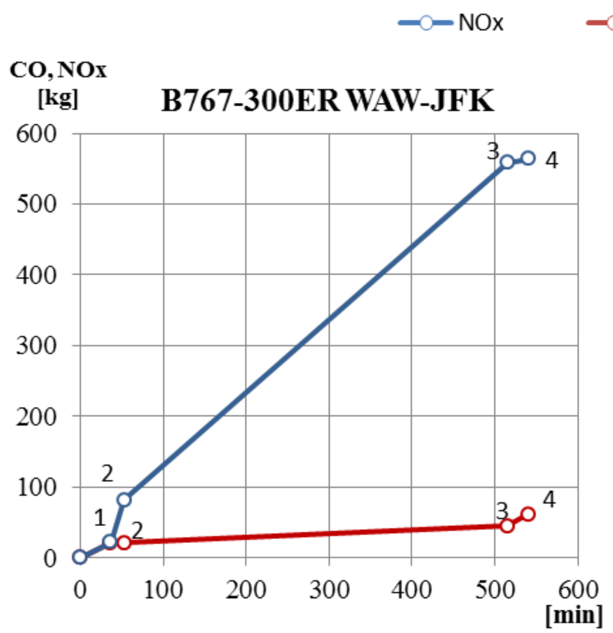

Fig. 5. CO and NO_x emissions on route from Warsaw to New York of the B767-300ER

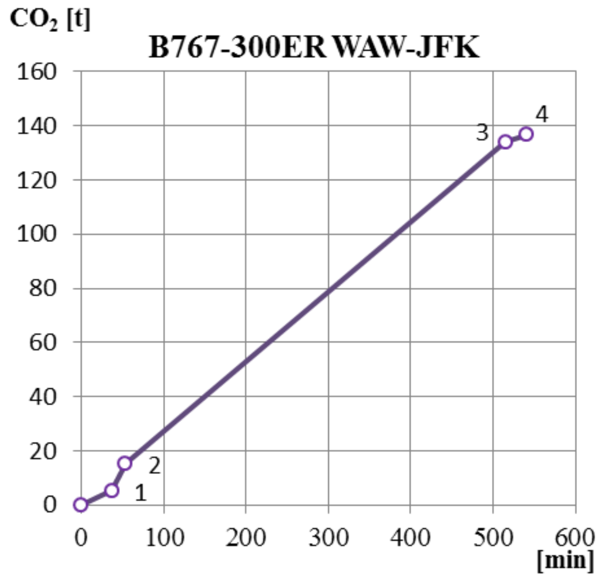

Fig. 6. CO_2 emission on route from Warsaw to New York of the B767-300ER

0-1 landing and take-off cycle, 1-2 climb from 3000 feet to the cruise altitude, 2-3 cruise, 3-4 descent to 3000 feet

3. Effect of engine deterioration on fuel consumption and NO_x emissions

Jet engine generates thrust in order to provide sufficient propulsion for the aircraft.

The performance of the power plant depends on several parameters, such as rotors speeds, fuel consumption and temperature. These parameters are monitored in order to ensure safe engine operations. One of the most critical parameters is the exhaust gas temperature (EGT) and its margin (EGTM) to a limit, called red line. During operations, engine performance deteriorates which leads to an increase in EGT and EGTM reduction. EGTM is always included by engine manufacturer or overhaul agency in the test-cell report as a vital parameter. Operator, based on its value can assess the production or overhaul quality of the engine. In addition to EGT, fuel consumption is another important jet engine efficiency parameter and during aircraft operations is measured as a fuel flow mass per hour (FF [kg/h]). In the test – cell is easy to calculate so called specific fuel consumption (SFC), which indicates how much fuel is burnt to produce certain amount of thrust:

$$SFC = FF/Thrust\ [kg/h/daN]. \tag{1}$$

Manufacturers of the engines in their technical publications concerning engine deterioration are providing information that reduction of EGTM by 10°C increases SFC by 0.7% [7].

From engine condition monitoring chart, shown in Fig. 8 (same engines are in Fig. 1), value of the $EGTM_{act.}$ is for certain known engines installed on specific airframe. It is easy now to calculate actual SFC value and fuel flow on max. thrust setting.

$$SFC_{act.} = SFC(0.1\ \Delta EGTM * 0.7), \text{ based on [7]}, \tag{2}$$

where:

$$\Delta EGTM = EGTM - EGTM_{act.}. \tag{3}$$

Figure 7 is a graphical presentation of EGTM definition.

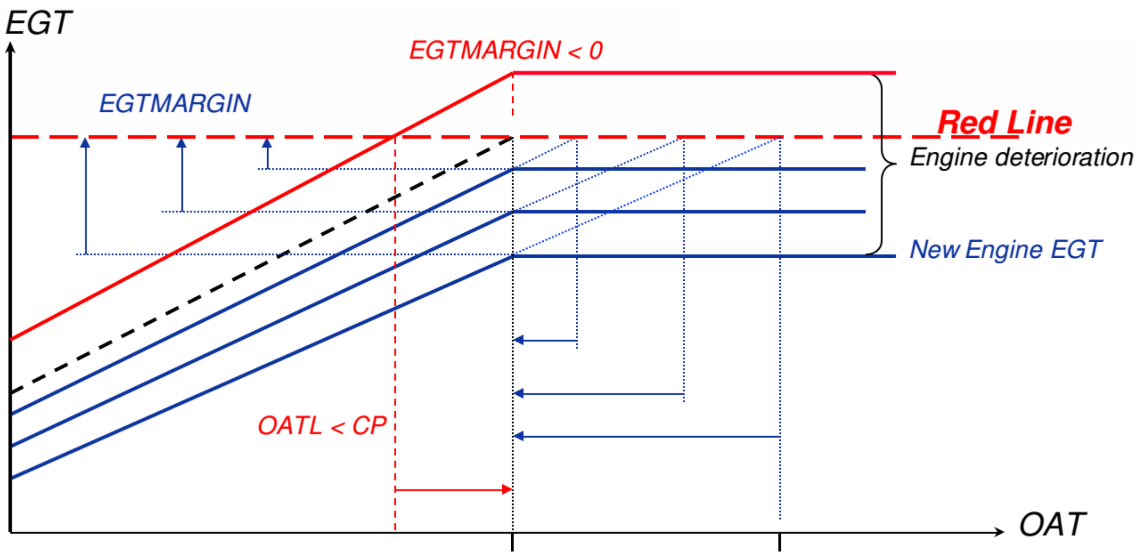

Fig. 7. Example of EGTM for a new and the deteriorated engine (based on [7]), OAT – Outside Air Temperature, OATL – Outside Air Temperature Limit, CP – Corner Point

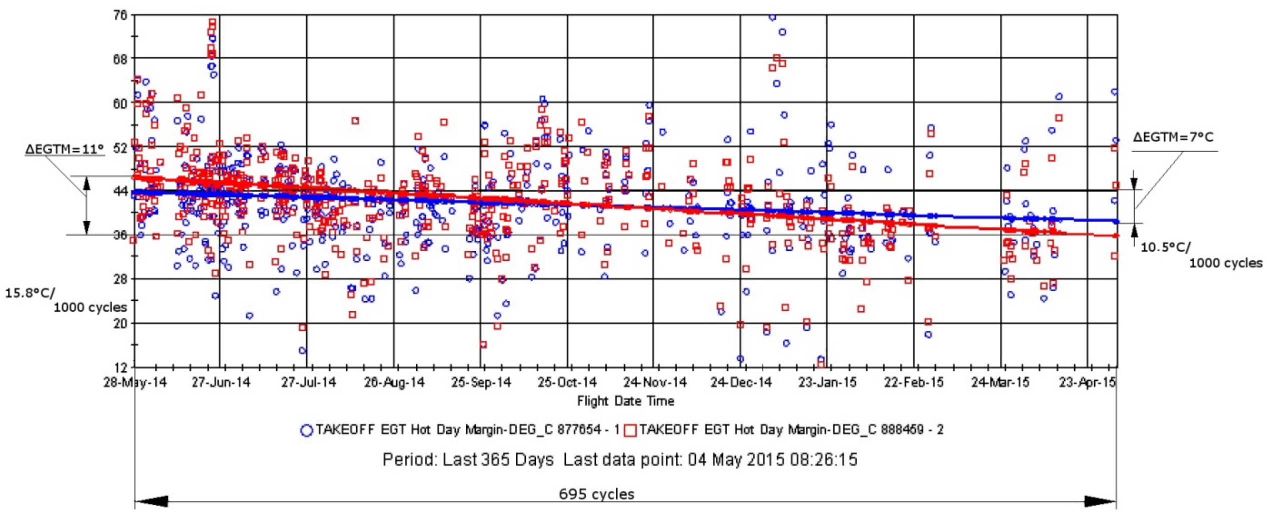

Fig. 8. Decrease of the EGTM of the CFM56-7B26 engines installed on B737-800 aircraft during one year of operations

Engines installed on the aircraft (Fig. 8) have S/N's: 877654 no. 1 and 888459 no. 2 and at present are on wing, 1991 cycles and 4455 cycles since last shop visit respectively.

After overhaul EGTM's for them were 67°C and 63°C and SFC's 0.386 [kg/h/daN] and 0.384 [kg/h/daN] accordingly. Now EGTM's are 38°C, 36°C, so using the equations (3, 2 and 1) fuel consumption (FF) actual values can be calculated, and they are 1.3 kg /s and 1.29 kg /s, respectively.

Considering all the above, new NO_x characteristics of deteriorated engines can be defined. Figures 9 and 10 are showing such characteristics based on test-cell data. In order of better graphical presentation, only higher power settings are considered. Equations of NO_x emissions are given only for deteriorated engines. Their test-cell equations can be found on Fig. 1.

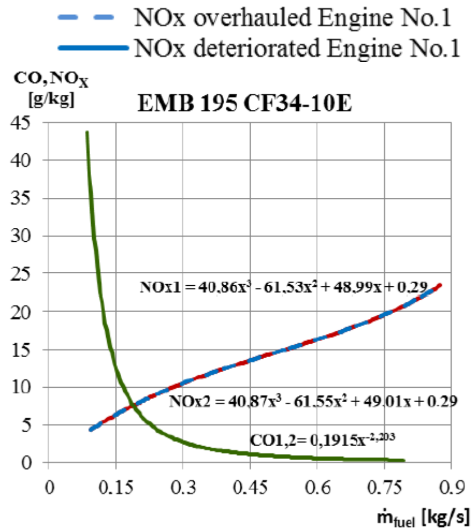

Fig. 9. Fuel consumption dependence from thrust taking into account engines deterioration

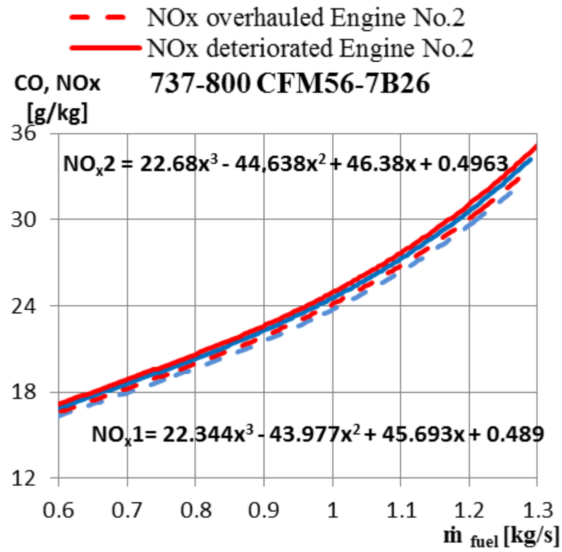

Fig. 10. NO_x emissions taking into account engines deterioration

Engine deterioration is a continuous process and update of emissions and fuel consumption values is proposed to be done every 500 cycles since engine installation on the aircraft. In our case calculations has been carried out after 1991 cycles for engine no 1 and 4455 cycles for engine no. 2. Fuel consumption has increased for engine no. 1 S/N 877654 in [kg/s] by 2% and for engine no. 2 S/N 888459 by 2.4%, compared to after overhaul test – cell results.

This is reflected in Fig. 11 by NO_x emission during B737-800 flight from Antalya to Wroclaw (CO is provided for reference).

Where NO_x emission of the aircraft after taking into account engines deterioration, has increased by 3.4% during climb from 3000 feet to cruise altitude; by 3.3% during cruise and by 3.5% during descent from cruise altitude to 3000 feet. NO_x emission has increased not proportionally to fuel consumption. The reason for this is that direct influence on NO_x creation has air-fuel mixture combustion temperature.

4. Effect of the jet stream on aircraft fuel consumption

Jet streams phenomenon on high altitudes has to be considered during flights planning.

Routes where high speeds of the jet streams have occurred were analysed. Results of calculations are presented in Fig. 12-17. Aircraft ground speed, heading, Mach number, jet stream direction and speed are known as they were registered by QAR.

From the below figures it can be seen that each 5 knots (10 m/s) of the jet stream axial component increases: 4 hours flight duration of the B737-400 by 9 minutes, and approx. 0.4 t of burned fuel. For 9 hours flight duration of the B767-300ER by 20 minutes and approx. 2.3 t.

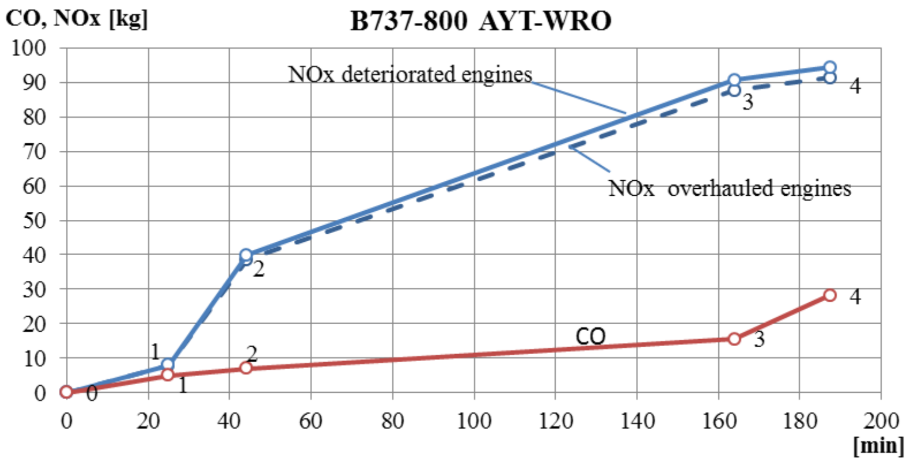

Fig. 11. NO_x emission during B737-800 flight while engine deterioration is taken into account: 0-1 landing and take-off cycle, 1-2 climb from 3000 feet to the cruise altitude, 2-3 cruise, 3-4 descent to 3000 feet

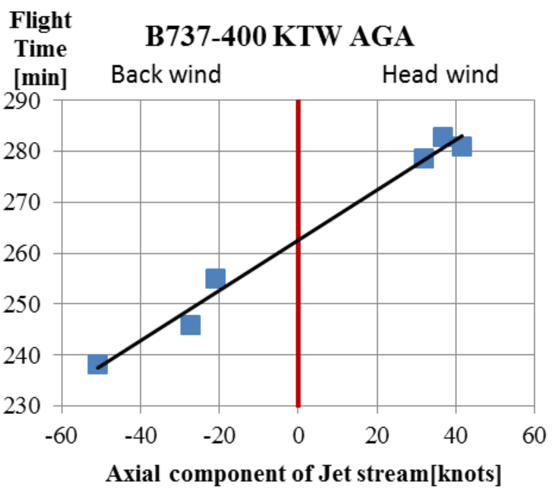

Fig. 12. Axial component value of the jet stream influence on B737-400 flight duration on route from Katowice to Agadir

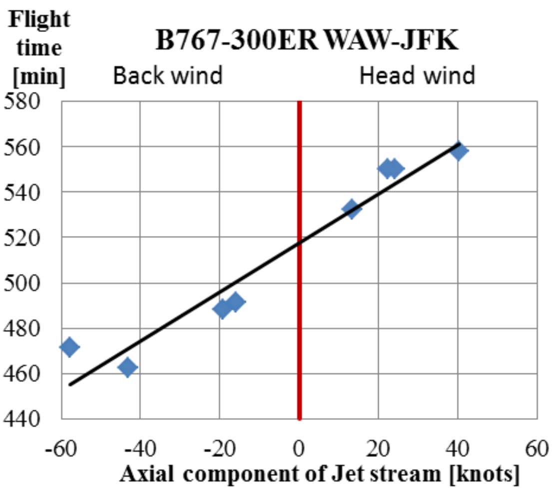

Fig. 13. Axial component value of the jet stream influence on B767-300 flight duration on route from Warsaw to New York

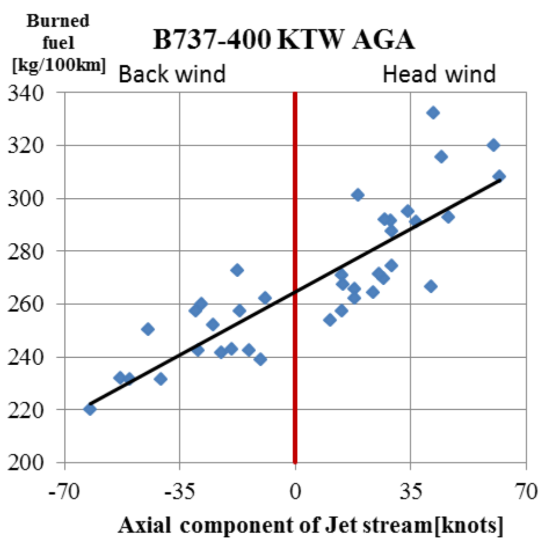

Fig. 14. Axial component value of the jet stream influence on B737-400 instantaneous fuel economy during flights from Katowice to Agadir

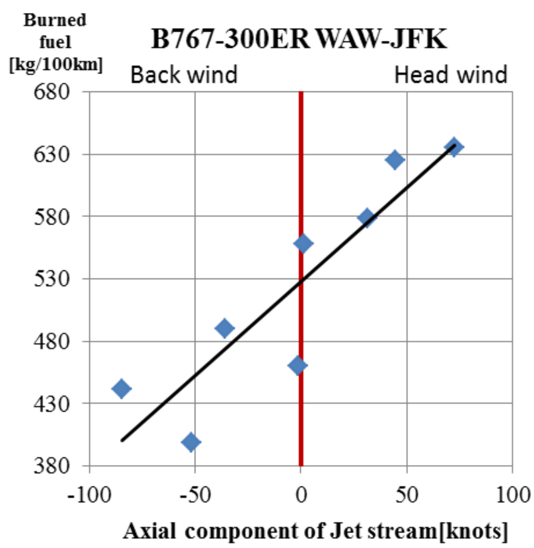

Fig. 15. Axial component value of the jet stream influence on B767-300 instantaneous fuel economy during flights from Warsaw to New York

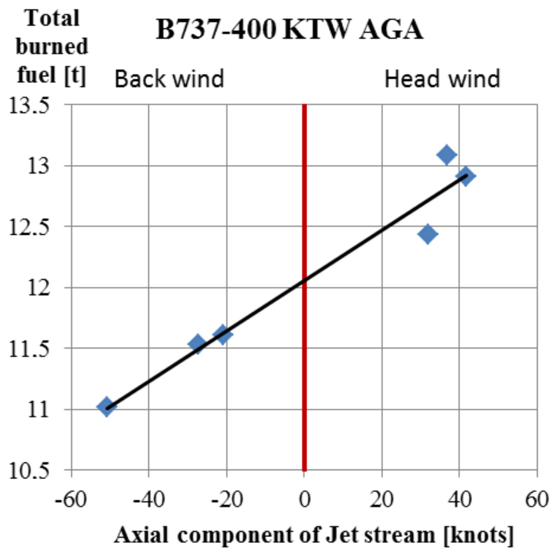

Fig. 16. Axial component value of the jet stream influence on B737-400 total fuel during flights from Katowice to Agadir

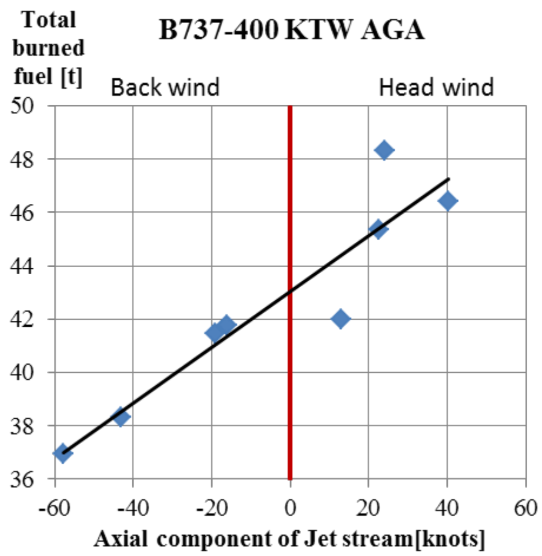

Fig. 17. Axial component value of the jet stream influence on B767-300ER total fuel consumption during flights from Warsaw to New York

5. Summary

Developed at the Institute of Aviation methodology usage of the data registered on the QAR, allows immediate emissions assessment of the CO_2, NO_x and CO on the any specified route for each aircraft type.

It also allows every Operator to determine important factors such as: fuel consumption per passenger, per seat or per one ton of freight during every flight phase.

Supports Operator's flight planning department and flight control in order to determine the cruise level that the head jet stream will be the smallest and back jet stream as big as possible.

Systematic fuel consumption increase by aircraft, for the same conditions is a signal to the Operator's technical staff to take steps in order to improve the engine performances, such as gas path wash, and even the decision to overhaul the engine.

Each aircraft with certain engines installed has to be treated individually while emissions and engines deterioration gradient is concerned.

The consequence of the depth analysis of the flights is improvement of the operating parameters of an aircraft and its power plants, which increases the safety of flying.

Not without significance are its positive effects on the environment and a positive impact on aircraft Operator economic performance.

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