ACEMIS: SOFTWARE FOR THE COMPUTATION OF AIRCRAFT FLIGHT EMISSIONS BASED ON FUEL CONSUMPTION

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ABSTRACT

The world has witnessed a significant growth in air traffic over the past 50 years. While this may be a good thing for a country's economy, increase in pollution and rise in temperature, due to the growth of greenhouse gas (GHG) emissions are worrying factors. Thus the methods to track pollutants emitted by flights, in order to mitigate the pollution, have become of utmost importance. ACEMIS (AirCraft EMISsion), presented in this paper, is a tool developed for the calculation of emissions based on fuel consumption of flights. The input data is one of the most important factors to create a realistic simulation and this paper explains how several influencing factors and actual flight data are considered for computation. It also explains the computational methodology to calculate the fuel consumption of a flight and simulate realistic emissions of not only carbon dioxide CO_2 but other gaseous emissions such as nitric oxides/nitrogen dioxide NO_x, water H_2O, carbon monoxide CO, hydrocarbons HC, and sulfur dioxide SO_2. This novel tool enables the user to simulate chemical emissions of a flight or a fleet between two or more airports, then displays and analyzes the simulation results. Finally, this calculation method is encoded using Python programming language to create a graphical friendly user interface.

Keywords: environment, aircraft, aeronautics, Python, greenhouse gas emission, GHG, pollution, carbon dioxide.

1 INTRODUCTION

The economic growth in the aeronautical sector, illustrated by novel airports creation (among others), has resulted in 8% increase in air traffic between 2014 and 2017, with a forecast of 42% increase from 2017 to 2040 [1]. The amplification of air traffic proportionally increases emissions of pollutants as fuel burn process in flight generates byproducts such as greenhouse gases (GHG). The significant emissions are carbon dioxide CO_2 (70% of the exhaust), water vapor H_2O (30%), sulfur dioxide SO_2, nitric oxide/nitrogen dioxide NO_x, carbon monoxide CO and hydrocarbons HC (around 1% of the exhaust combined). There are many studies focusing on the impact of CO_2 onto the environment, whereas other flight emissions have been historically ignored. This has to change in order to act significantly against the negative impact of the aeronautic sector on the environment. The United Nations' Intergovernmental Panel on Climate Change (IPCC) published one of the first reports on the impact of non-CO_2 emissions in 1999 highlighting the contribution of NO_x at high altitudes in the depletion of ozone layer [2]. Water vapor forms cirrus-clouds at high altitude, which has a serious warming effect despite its short life span because of the collective effect of thousands of continuous flights [3]. The climate impacts of NO_x, contrails, and clouds due to H_2O emitted at high altitude is so strong that they can eat the planet more in one day than all the aviation's CO_2 accumulated in the atmosphere since the 1940s [4]. Hence, it has become increasingly important today and in the future to keep a record on GHG and/or pollutant emissions like H_2O, SO_2, NO_x, CO and HC, in addition to CO_2.

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CO_2 emissions from aviation have been included in the EU emissions trading system (EU ETS) since 2012. Under the EU ETS, all European and non-European airlines operating in Europe are required to monitor, report, and verify their emissions, then they may have to pay allowances against those emissions. Every year, they receive tradeable allowances covering a certain level of emissions from their flights [5]. In 2016, the International Civil Aviation Organization (ICAO) agreed on a resolution for a global market-based measure to address CO_2 emissions from international aviation as of 2021 [6]. The agreed resolution sets out the objective and key design elements of the global scheme, as well as a roadmap for the completion of the work on implementing modalities. The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) program aims to stabilize CO_2 emissions at 2019 levels by requiring airlines to offset the growth of their emissions after this date [6]. It however takes into account only CO_2 emission.

To respect the regulation as set out by ETS or CORSIA, airlines must keep tracking all types of emissions contributing to global warming. Even though methods are proposed to gather the in-flight emissions data [7], there is currently no complete tool for the calculation of flight emissions other than CO_2 [8]. To fill this gap and anticipate the future of aviation, the Capgemini Engineering group envisioned an emission and fuel consumption-tracking graphics friendly user interface (GUI) tool called ACEMIS (AirCraft EMISsions). It uses scientific calculation methodologies to simulate the fuel consumption and flight emissions (CO_2, NO_x, H_2O, CO, HC, SO_2) in two ways, one by using MOZAIC or IAGOS data [9] from flights that have already taken place ("MOZAIC/IAGOS Fleet" part in the tool), and the other by building personalized flight routes ("Flight Profile" part in the tool, Fig. 1).

MOZAIC (Measurements of OZone, water vapor, carbon monoxide and nitrogen oxides by in-service AIrbus airCraft) is an observation program that took place between Aug. 1994 and Nov. 2014 [9]. Its purpose was to measure the composition of the atmosphere through commercial aircraft of various airlines. Several chemical components have been recorded: ozone (O_3), carbon monoxide (CO), water vapor (H_2O) and total nitrogen oxides (NO_y). IAGOS (In-service Aircraft for a Global Observing System), which started in Jul. 2011 until today, is the continuation of the MOZAIC program and includes among others measurements of ozone (O_3), carbon monoxide (CO), water vapor (H_2O), nitrogen oxides (NO_x, NO_y) and greenhouse gases (CO_2, CH_4) [9]. All measurements are geo-localized (latitude, longitude, altitude…) and supplemented by meteorological data (temperature, pressure, humidity…).

2 METHODOLOGY

ACEMIS is a GUI software that calculates the fuel consumption and pollutant emissions. The user can enter flight information such as flight name, aircraft type, fuels used (and their concentration), weather conditions, departure and arrival airports, and passenger fill rate of the aircraft (Fig. 1). Realistic simulation can be done in the MOZAIC/IAGOS module using real flight data received from MOZAIC or IAGOS database [9], whereas personalized flight routes are simulated in the FLIGHT PROFILE module. The right part (red dashed line, Fig. 1) displays useful information such as fleet, progress of the simulation (inside the red dotted box) and the information of the selected flight.

In this section, the methodologies behind the fuel consumption and emissions calculation are explained.

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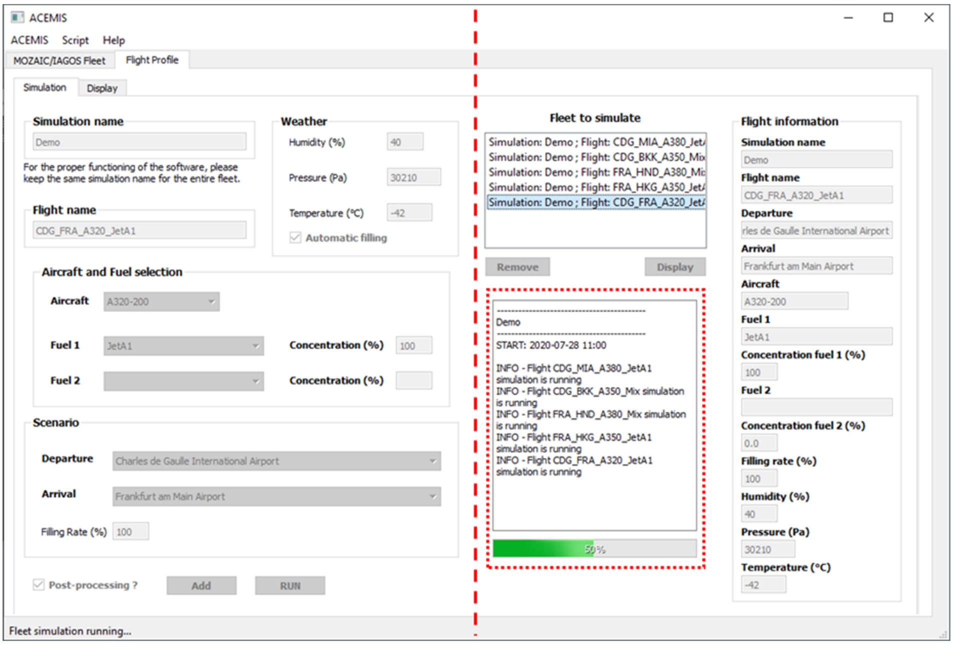


Figure 1: Graphical user interface of ACEMIS – version 2.1 – Flight Profile part.

2.1 Calculation of fuel consumption

The fuel consumption calculation requires data from the Auxiliary Power Unit (APU) and the engine: the standard thrust on the ground Tr_{00}, the specific consumption SFC_{00}, the fuel flow at idle speed FF_{IDLE}, and the fuel flow of the APU FF_{APU}. These data, together combined with the "aircraft" parameters and ambient conditions, make possible to calculate the rate of fuel burned by the aircraft at any point.

The fuel flow is the product of the specific fuel consumption and the thrust. Thrust is calculated differently depending on whether the aircraft is stabilized in the cruise phase, the climb phase, or the braking phase (this is referred as back thrust, eqns (1)–(3)). In the first case, the thrust is determined from the balance of forces acting on the aircraft; in the second case, an empirical method is used.

$$\begin{cases} SFC(z,M) = SFC_{00} \times \sqrt{T(z)/T_{00}} \times (1+M). \\ Tr(z,M) = Tr_{00} \times (0.568 + [0.25 \times (1.2-M)^3]) \times [P(z)/P_{00}]^{0{,}6}. \\ FF(z,M) = SFC(z,M) \times Tr(z,M). \end{cases} \quad (1)$$

$$\begin{cases} SFC(z,M) = SFC_{00} \times \sqrt{T(z)/T_{00}} \times (1+M). \\ Tr\left(m_{A/C}\right) = \left(m_{A/C} \times g_0\right) \times [\cos\beta/f - \sin\beta]/nb_{eng}. \\ FF(z,M) = SFC(z,M) \times Tr(z,M). \end{cases} \quad (2)$$

$$\begin{cases} SFC(z,M) = SFC_{00} \times \sqrt{T(z)/T_{00}} \times (1+M). \\ Tr(m_{A/C}) = m_{A/C} \times (V_{INV}/t_{T-D})/nb_{eng}\,. \\ FF(z,M) = SFC(z,M) \times Tr(z,M). \end{cases} \tag{3}$$

where:

- Atmospheric parameters: *T* (temperature; K), *P* (pressure; Pa), *RH* (relative humidity);
- Aircraft parameters: *FF* (fuel flow; $kg.s^{-1}$), *Tr* (thrust; N), *SFC* (specific consumption), *M* (Mach number), *m* (mass; kg), nb_{eng} (number of engines), V_{INV} (reverse speed; $m.s^{-1}$), t_{T-D} (duration of braking phase; s);
- Indices: 00 (ground condition), *eng* (engine), *APU* (Auxiliary Power Unit), *IDLE* (idle phase), *A/C* (aircraft);
- Other: g_0 (acceleration due to gravity = 9.80665 $m.s^{-2}$), γ (isentropic coefficient of air = 1.4), *r* (specific ideal gas constant = 287.058 $J.K^{-1}.kg^{-1}$), *f* (finesse = ration of coefficient of lift and drag; four possible configurations, noted from f_0 to f_3), β (descent slope of the aircraft).

When using the *APU* during the parking phase, the fuel flow denoted FF_{eng} and expressed in kg/s, can be summed up as follows in eqn (4):

$$FF_{eng} = FF_{APU}. \tag{4}$$

Similarly, at idle speed, the fuel flow is provided by the ICAO data (eqn (5)):

$$FF_{eng} = FF_{IDLE}. \tag{5}$$

2.2 Calculation of emissions

Calculation of emissions requires the fuel flow value. The product of the fuel flow and the emission indices (ratio of mass of pollutant emitted and mass of fuel consumed) allows the calculation of the emission of the pollutant considered per unit of time during a flight. These calculations are done based on two methods: first, the complete combustion assumption for CO_2, H_2O and SO_2 emissions, and second the Boeing Fuel Flow Method (BFFM2 method) for NO_x, CO and HC [10].

$$\begin{cases} EI(CO_2) = m_C \times (M_C + 2.M_O)/(M_C). \\ EI(H_2O) = m_H \times (M_O + 2.M_H)/(2.M_H). \\ EI(SO_2) = m_S \times (M_S + 2.M_O)/(M_S). \end{cases} \tag{6}$$

where:

- fuel parameters: *m* (mass percentage of a compound; kg/kg), *M* (molar mass of a compound; $g.mol^{-1}$);
- Indices: C (carbon), H (hydrogen), O (oxygen), S (sulfur).

The BFFM2 method consists in extrapolating the emission indices at an altitude from the emission value on the ground affected by the ambient conditions – temperature, pressure and humidity [10]. This is done in three steps:

1. The calculation of fuel flow rate on the ground determined from the previously calculated consumption (FF_{eng}), the ambient conditions (*T*, *P*) and the speed of the aircraft (*M*), eqn (7):

$$FF_{00} = FF_{eng} \times \frac{(T/T_{00})^{3,8}}{(P/P_{00})} \times e^{0,2\times M^2}. \quad (7)$$

2. Linear interpolation of ICAO data using above value to associate it with emission indices $EI_{NOx,00}$, $EI_{CO,00}$, and $EI_{HC,00}$
3. Calculation of the aircraft's emission indices (eqn (8)) using the values obtained from step 2 above (in the absence of relative humidity data, the value of 50% is applied).

$$\begin{cases} EI_{NOx}(z) = EI_{NOx,00} \times ((T/T_{00})^{3.3}/(P/P_{00})^{1.02})^{-0.5} \times e^{-19(q-0.00634)}. \\ EI_{CO}(z) = EI_{CO,00} \times \sqrt{((T/T_{00})^{3.3}/(P/P_{00})^{1.02})}. \\ EI_{HC}(z) = EI_{HC,00} \times \sqrt{((T/T_{00})^{3.3}/(P/P_{00})^{1.02})}. \end{cases} \quad (8)$$

where:

- Aircraft parameters: *EI* (emission indice of a pollutant; kg/kg), *FF* (fuel flow rate; $kg.s^{-1}$), *M* (Mach number at an altitude z);
- Atmospheric parameters: *T* (temperature; K), *P* (pressure; Pa), *q* (specific humidity);
- Indices: 00 (ground parameter), *eng* (in-flight parameter).

3 SIMULATION RESULTS

In ACEMIS, the results could be analyzed under the "Display" tab. Within the sub-tab of "Flight" the result of one single flight can be displayed (Fig. 2). For the purpose of demonstration, the results of the flight trajectory, fuel flow rate, and emissions graph of CO_2, CO, and NO_x in Fig. 2 are displayed for a flight from Paris Charles de Gaulle International Airport to Miami International Airport with an A380-800 aircraft, 100% JetA1 fuel and 99% passenger fill rate. The weather conditions are the same as the cruise conditions.

From Fig. 2(b), the maximum fuel burn (ca. 7 $kg.s^{-1}$) is reached during take-off and landing phases, which in turn produces more emissions (concentrated on a brief period of time, compared to the total time flight). At cruise, the fuel consumption is ca. 2 $kg.s^{-1}$. From Fig. 2(c), the CO_2 emissions are ca. 22 $kg.s^{-1}$ during the take-off and landing phases, while it stabilizes at ca. 7 $kg.s^{-1}$ at cruise, correlated with the fuel consumption profile (Fig. 2(b)). Both fuel consumption and CO_2 emissions are about three times more important in the take-off and landing phases. Based on Fig. 2(d), the CO emission is ca. 0.0085 $kg.s^{-1}$ for the take-off and landing phases, while it stabilizes at ca. 0.0022 $kg.s^{-1}$ at cruise. Here again, CO emission during take-off and landing is nearly four times more than the cruise level. The same observation is made from Fig. 2(e), where NO_x emissions are ca. 0.5 $kg.s^{-1}$ during take-off and landing phases, while it stabilizes at ca. 0.04 $kg.s^{-1}$ at cruise. Thus, NO_x emissions during take-off and landing are about 12 times increased compared to the cruise level.

Within the sub-tab "Fleet", the results of all the simulations at the same time are depicted if the post-processing option was ticked. Then, the consumption and emissions statistics of the entire fleet simulated are also depicted. For the purpose of demonstration, a fleet of five flights was created, depicted in Table 1 (refer to Fig. 1 to see the ACEMIS graphic interface while fleet simulation is running).

The fuel consumption and CO_2 emissions distribution of the above fleet are shown in Fig. 3: there is a high fuel consumption and CO_2 emission region near departure and arrival airports (green region, Fig. 3(a) and (b)), corresponding to the take-off and landing phases.

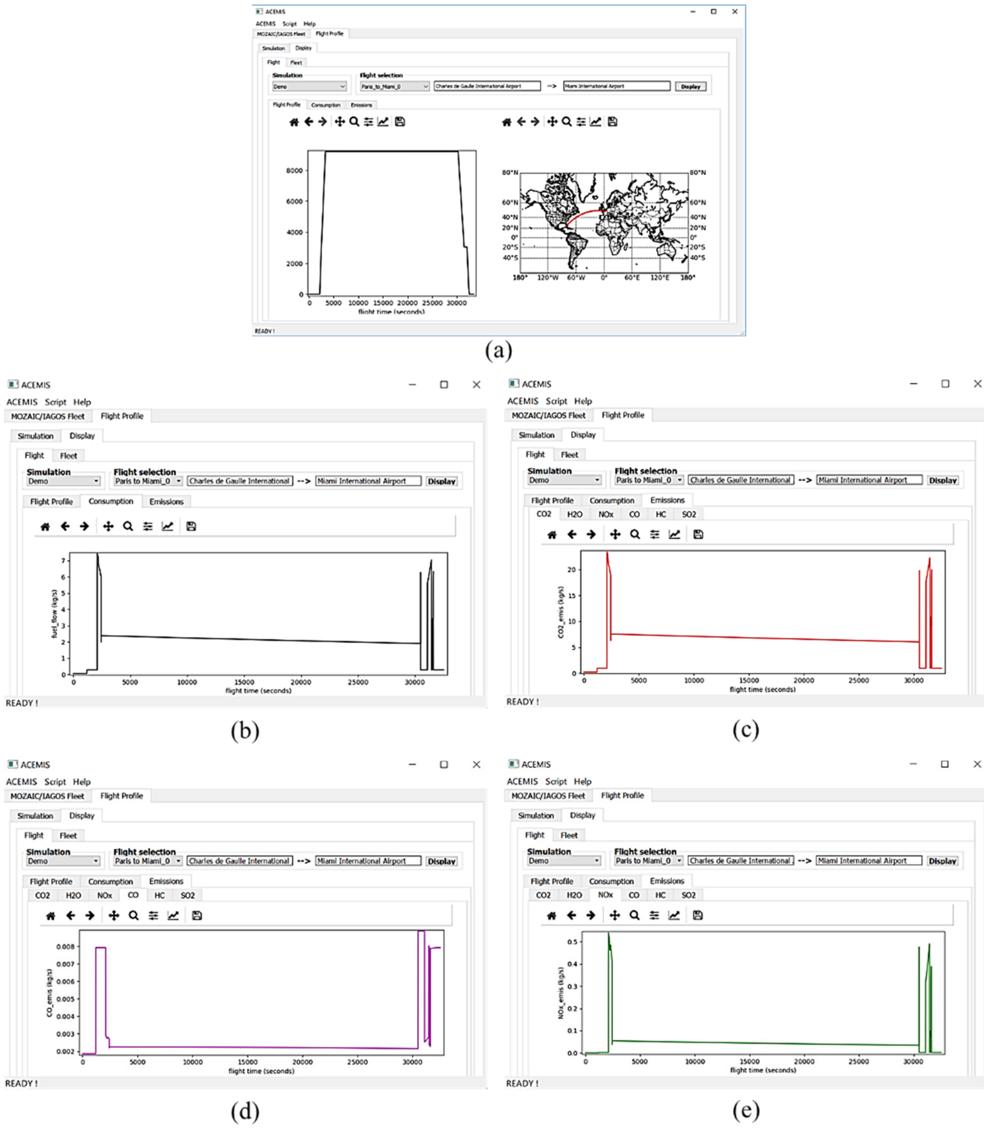
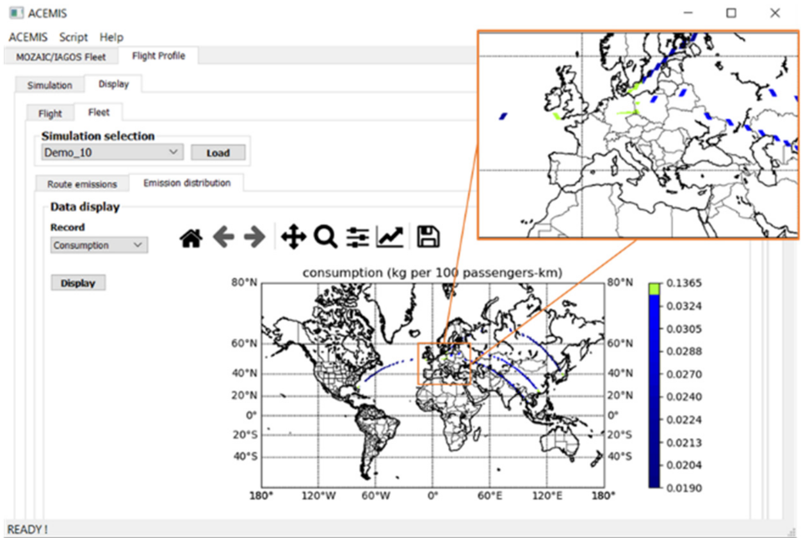


Figure 2: Display menu of "Flight Profile" part. (a) Flight altitude (left part) and orthodromic projection of the flight route on the map (right part); (b) Fuel consumption; (c) CO_2 emissions; (d) CO emissions; and (e) NO_x emissions, as a function of flight time.

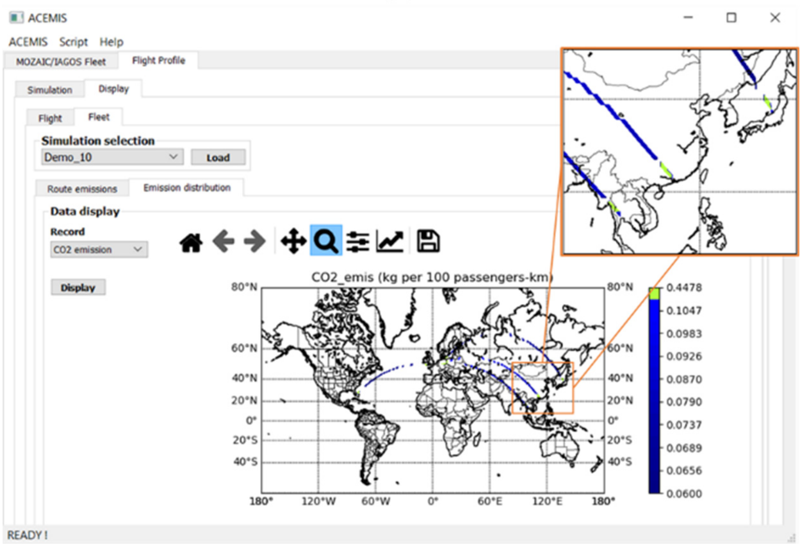
The potential of the ACEMIS tool is depicted Fig. 4 hereafter: it shows the geographical distribution and intensity of CO_2 emissions over a sample of approximately 10,000 flights from Frankfurt International Airport in Germany (based on the MOZAIC/IAGOS database).

Table 1: Fleet simulation of five flights in ACEMIS.

	Flight 1	Flight 2	Flight 3	Flight 4	Flight 5
Simulation name	Demo_10	Demo_10	Demo_10	Demo_10	Demo_10
Flight name	CDG_MIA_ A380_JetA1_10	CDG_BKK_ A350_Cat1_10	FRA_HND_ A380_Cat1_10	FRA_HKG_ A350_JetA1_10	CDG_FRA_ A320_JetA1_10
Aircraft	A380-800	A350-900	A380-800	A350-900	A320-200
Fuel 1	JetA1	–	–	JetA1	JetA1
Concentration fuel 1 (%)	100	–	–	100	100
Fuel 2	–	Catalytic cracking bio oil n°1	Catalytic cracking bio oil n°1	–	–
Concentration fuel 2 (%)	–	100	100	–	–
Departure Airport	Charles de Gaulle	Charles de Gaulle	Frankfurt-am-Main Airport	Frankfurt-am-Main Airport	Charles de Gaulle
Arrival airport	Miami International	Suvarnabhumi Airport	Tokyo Haneda International	Hong Kong International	Frankfurt-am-Main Airport
Filling rate	99%	90%	99%	90%	100%
Humidity (%)	32.3	40	35	38.5	40
Pressure (Pa)	26,838	28,439	31,892	27,485	30,210
Temperature (°C)	–48	–51	–46	–49	–42
Post-process?	Yes	Yes	Yes	Yes	Yes



(a)



(b)

Figure 3: Display menu of "Flight Profile" part – Geographical distribution of (a) fuel consumption; (b) CO_2 emissions along the fleet routes.

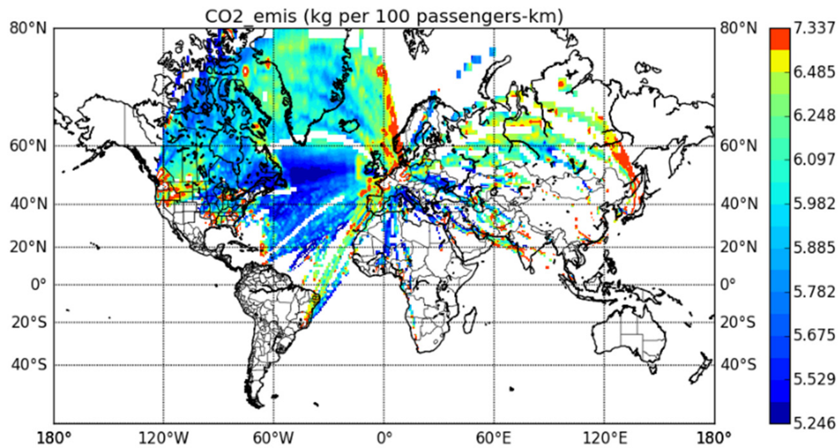


Figure 4: Display menu – Geographical distribution of CO_2 emission over a sample of approximately 10,000 flights.

4 DISCUSSION

In order to validate the ACEMIS emissions model, a comparison with free and available calculators were done. ICAO has provided an online carbon emission calculator tool for CO_2 emissions of a flight [11]. Furthermore, the CORSIA program has developed a tool called CO_2 Estimation and Reporting Tool (CERT) [12], with more options about aircrafts, fuels and other parameters compared to the ICAO online simulator. Similarly, in France, the *Direction Générale de l'Aviation Civile* (DGAC) put in place an online carbon emission calculator known as TARMAAC (which stands for *Traitements et Analyses des Rejets éMis dans l'Atmosphère par l'Aviation Civile*) [13].

Hereafter, Table 2 represents the comparison between ICAO online calculator, CERT tool from CORSIA program, and ACEMIS for the fuel consumption and CO_2 emissions related to the same flight profiles. The results show the same degree of magnitude for the total fuel consumption and the CO_2 emissions. The ICAO calculator does not take all the parameters for the flight simulation, such as the aircraft used, the type of fuel, the weather data or the passenger-filling rate of the aircraft [11], whereas the CERT from CORSIA and ACEMIS do. In addition, ICAO calculator assumes that all aircrafts are entirely configured with economic seats. The values calculated are an average of the type of aircrafts, fuel used, and passenger fill rate information, available in the ICAO database [11]. Since JetA1 fuel is the most common fuel used today, it is assumed that the ICAO simulations are based on flights operating with 100% JetA1, so the same conditions were chosen with the CERT and ACEMIS. Therefore, ICAO results are approximated via several factors. On the other hand, the CERT seems to approximate the fuel used during the flights, as well as the CO_2 emissions calculation (Table 2). ACEMIS results may be closer to reality, thanks to the calculations done in each flight segment, and experienced with the MOZAIC/IAGOS database [9]. Each ACEMIS simulation is specific to a single aircraft and engine, depending on various parameters. The results therefore are varying realistically, depending on the type of aircraft and its characteristics.

Table 2: Results of CO_2 emissions calculated with ICAO online simulator, CERT_CORSIA (simulator tool from CORSIA program), and ACEMIS v2.1 about multiple flights comparison. Fuel: 100% JetA1; Paris stands for Charles de Gaulle International Airport, New York for John F. Kennedy International Airport, Shanghai for Shanghai Pudong International Airport, Vienna for Vienna International Airport, and Dubai for Dubai International Airport.

		ICAO online simulator			CERT_CORSIA			ACEMIS v2.1		
Flight	Aircraft	Total fuel consumption (kg)	Total emissions CO_2 (kg)	Emissions CO_2/Fuel consumption	Total fuel consumption (kg)	Total emissions CO_2 (kg)	Emissions CO_2/Fuel consumption	Total fuel consumption (kg)	Total emissions CO_2 (kg)	Emissions CO_2/Fuel consumption
Paris–New York	A330-300	55,014.7	98,193.6	1.78	41,000.0	131,000.0	3.20	49,239.7	155,449.8	3.16
Paris–New York	A380-800	55,014.7	178,057.7	3.24	88,000.0	279,000.0	3.17	74,356.0	234,741.8	3.16
Paris–Shanghai	A330-200	88,673.9	97,953.6	1.10	63,000.0	200,000.0	3.17	63,099.3	199,204.6	3.16
Paris–Shanghai	A380-800	88,673.9	215,735.9	2.43	142,000.0	449,000.0	3.16	116,958.2	369,237.1	3.16
Paris–Vienna	A320-200	5,414.5	16,922.6	3.13	8,000.0	26,000.0	3.25	5,274.7	16,652.2	3.16
Paris–Vienna	E190	5,414.5	10,830.5	2.00	3,000.0	9,000.0	3.00	2,968.1	9,370.3	3.16
Paris–Dubai	A330-200	78,847.6	82,321.8	1.04	36,000.0	113,000.0	3.14	35,457.9	111,940.5	3.16
Paris–Dubai	A380-800	78,847.6	181,308	2.30	80,000.0	252,000.0	3.15	67,496.6	213,086.9	3.16

5 CONCLUSION

There is today a global consensus that climate change can be largely imputed to human activities, and that our society should move towards sustainable and renewable energy sources. ACEMIS tool is contributing towards aircraft traffic related pollution reduction. ACEMIS can be useful to airlines in many ways:

- for diagnosis purpose and continuous improvement of their environmental footprint, not only based on CO_2 emissions, but also considering other pollutants to estimate the global impact of their fleet activity;
- to enable airlines to not only comply with the environmental requirements (such as the CORSIA program), but also to prevent further environment restriction based on the other chemical pollutants.

This is equally helpful to the regulatory bodies in the aviation sector (e.g. DGAC/DSNA in France), engineers, and environmental auditors (among others) to analyze the emissions levels. It also leads to the awareness of interested party about the most/the least polluted regions, along the flight path. This in turn could help to schedule future routes as avoiding climate sensitive regions might be the most promising approach to reduce the climate impact of non-CO_2 emissions [14].

ACEMIS is a scalable tool developed using Python programming language. Due to the independent nature of the modules, the future aircraft technologies affecting the simulation can be easily integrated within existing or novel modules. With a simple update of the database files, it is possible to integrate new aeronautics developments, such as disruptive aircraft design, novel engines, biofuels, electricity and hydrogen technologies… The Capgemini Engineering group is currently working on new features such as simulation of noise around airports, inclusion of emission simulation of cargo flights, 3D results display and inclusion of electrical and hydrogen powered engines, in order to provide one of the first pollutants simulation of these novel technologies. The final objective is to get a solution that is beneficial to future users, thanks to quick updates and easy integration of new technologies.

6 SOFTWARE AVAILABILITY

Name: ACEMIS.
Developer: Capgemini Engineering.
Contact: Capgemini Engineering (www.altran.com).
Programming framework: Python.
Language: English.
Year first available: 2021.

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