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PROMISING TECHNOLOGIES TO REDUCE GLOBAL AND LOCAL AVIATION EMISSIONS

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Summary. This document provides information and instructions for preparing a Full Paper to be included in the Proceedings of *ECCOMAS 2024 Congress*

1. NTRODUCTION

Climate change is the megatrend that will have the biggest impact on the development of sustainable air transportation in near future. Pioneering sustainable technology is allowing the civil aviation sector to embrace the next generation of aviation through electrification and alternative fuels including hydrogen. If to look at new supersonic aircraft future technologies are considered in mostly traditional development of emission reduction in combination with SAF for fuel burn by their engines (as considered now by EU SENECA project).

Radically new innovative aircraft concepts are necessary for implementation in aircraft design, which efficiency in emission reduction should be much higher than for current evolutionary concepts. The electrification of aircraft propulsion promises a significant reduction of aviation emissions and progress toward the strategic goals achievement. The first recommendation for EU EFACA project relates to the implementation of hybrid electric propulsion technology for propeller-driven regional aircraft. Principles of aircraft hybrid electrification should be enough for necessary emission reduction of GHGs by regional aircraft in flight, so as the goals in aircraft noise and local air quality should be reached.

Hydrogen fuel, which is burnt in combustion chambers of the engines directly (instead of usual fossil fuel or/and SAF from renewable resources), is the crucial potential technology for eliminating aircraft GHG emissions for the most popular groups of aircraft – short/medium range and long-range aircraft (their contribution in aviation sector is over the 90 %). With hydrogen as a fuel, either in combustion engines or used in a fuel cell, there are no in-flight CO_2 emissions whatsoever. The second recommendation for EU EFACA project relates to the implementation of hydrogen fuel cells and liquid hydrogen fuel system for propeller-driven regional aircraft and jet airliner correspondingly.

2 AIRCRAFT FUEL CONSUMPTION AND ENGINE EMISSION REDUCTION TECHNOLOGIES

Global aspiration goal for climate change was adopted by ICAO in 2010 and aimed to fuel efficiency improvement of feet on 2% per annum from 2020. Additionally, Independent Experts (IE) in part of integrated technology goals assessment and review for engines and aircraft recommended the following goals: 1,38% per annum for the SA (Single Aisle Aircraft) and 1,43% per annum for TA (Twin Aisle aircraft) [1]. In principle, the technologies in part of fuel reduction could be separated into airframe (aerodynamic and mass) and engines, fig.1.

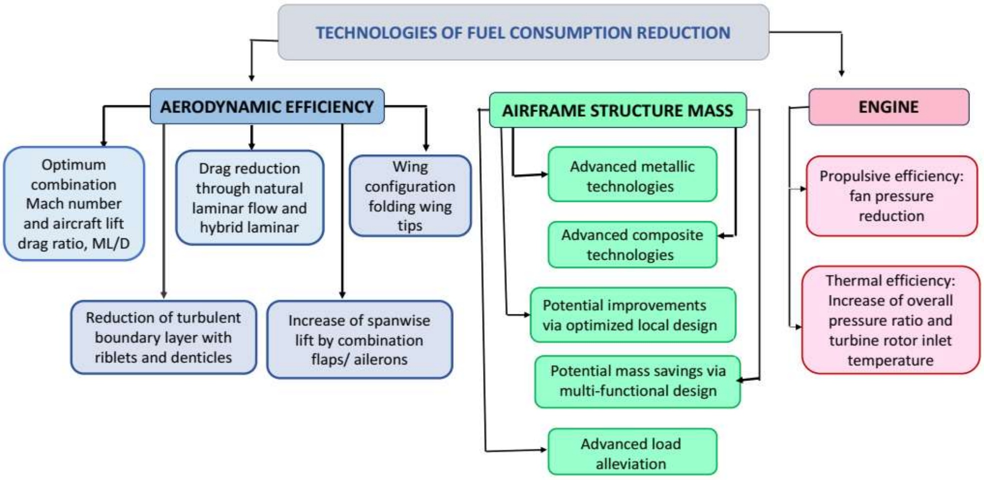

Fig.1. Fuel consumption reduction technologies

Analysis of the studies [2-5] studies has demonstrated fuel burn assessment of the individual technologies for different aircraft groups. In general, rolled-up engine technologies contribute larger fuel burn benefits that aerodynamic and structural technologies only. The plot (fig.2.2) demonstrates the trends of fuel saving in new design fuel efficiency for considered aircraft groups. The fully deploy effective technologies identified for new aircraft design would reduce fuel consumption on 20%.

3. METHODOLOGY FOR EMISSION CALCULATION

The PolEmiCa complex model (developed at NAU in 2013, verified at CAEP/ICAO in 2020) implements the $BFFM_2$ method for calculating emission indices. To perform the research tasks for the conventional and hybrid turboprop engine, the module for calculating the emission indices based on the $BFFM_2$ method was improved. This module takes into account flight path parameters (altitude, Mach number, aircraft speed), operational parameters (real fuel consumption) and meteorological conditions (humidity, temperature, atmospheric pressure).

The **BFFM2 method is adopted** several stakeholders not only for the evaluation of the emissions in cruise, but also for the estimation of the overall amount of pollutants emitted by a aircraft throughout an entire reference trajectory, as well as to support the generation of 3D emission inventories and the consequent evaluation of the impact of aviation on climate change.

The BFFM2 method presents some uncertainties that must be included in part of clarification of prediction emission indices. Although there are no problems with the NOx prediction, as reported by Kim and Rachami [6], Wood et al. [7], the computation of HC and CO can be quite challenging. Thus, for the throttle setting is less than 7% (for low fuel flow values) recalculation of EIHC, EICO for reference conditions can obtain in unrealistically high values. According to Lee [8], a study conducted by ICAO found an agreement between direct measurements and estimated fuel flow “with a standard deviation of 6% and a maximum error of 13%”.

4. REFERENCE AIRCRFT EMISSION MODEL FOR THE NOVEL HEP TURBOPROP AIRCRAFT

EFACA project is focused on the development of new technologies by using electric and hybrid thermoelectric propulsions and new sustainable fuel to replace fossil fuel. Crucial technologies in part of engine relates with 2 aircraft groups:

1. **regional aircraft** is intended for hybrid turboelectric power in combination with fuel cells (reference aircraft – **ATR 72-600);**
2. **jet-powered narrow-body airliner** is intended for the operation of hydrogen–fuelled gas turbines **(reference** aircraft – **A320neo).**

4.1 Flight profile for the conventional and hybrid ATR 72-600 (AT76)

The trajectory for AT75 with hybrid and conventional power plant were modelled by team of Acoustic Lab NAU. In contrast to existing methods for calculating the flight path the improved method made it possible to fulfill the operational limitations and reliably predict the speed, altitude, fuel consumption, thrust, pitch angle of the aircraft in the form of continuous functions of time throughout the flight profile. The presence of these functions is the basis for calculating the emission of pollutants [9]. Trajectories were calculated in full compliance with the AT76 flight operation manual for both the conventional and hybrid versions of the aircraft, because the aerodynamics of the aircraft remained unchanged. The flight profiles were modelled for the maximum range for both the conventional and hybrid AT76 correspondingly 4133 km and 3854 km (both with contingency fuel reserve of 500 kg fuel and 30kg of unusable fuel). The thrust, speed and height distribution along the flight profile are shown on fig.2.

The excess weight associated with the installation of additional batteries, electric motors, gearboxes, modernization of the exhaust system, cooling and additional cables was subtracted from the fuel weight without reducing the payload (5150 kg). The specified operational parameters (including fuel flow rate) were modeled on the basis of the module for calculating the flight profile of aircraft with conventional and hybrid PSs [10] and a module for calculating the working process of gas turbine engines.

4.3. Modeling of the mass of fuel burned and gaseous emissions throughout a flight profile for AT75 with conventional and hybrid power plants (*global emission impact*)

For the calculation the **mass of fuel burned and gaseous emissions** for the AT76 type aircraft with conventional and hybrid power plants, operational and meteorological data were provided regarding:

1) flight trajectories (altitude, distance, speed, Mach number) of an aircraft with conventional and hybrid PS, Fig.2;

2) the ratio of fuel and air in the combustion chamber of an aircraft engine;

3) meteorological parameters – temperature, humidity, and atmospheric pressure were estimated in accordance with manual of ICAO standard atmosphere (ICAO Doc 7488/3 [11].

The improved module for calculating emission indices by combining the module for calculating the parameters of the flight path and the results of calculating the thermogas-dynamic calculation of the aircraft engine makes it possible to detect the influence of fuel consumption (engine thrust) on the values of emission indices. This feature is representative for evaluating the efficiency of hybrid engines because the electrification of the aircraft fleet is primarily aimed at reducing fuel consumption.

Comparison of modeling results for the AT76 type aircraft with conventional and hybrid power plants for the throughout flight profile concludes, that application of electric motors at take-off, climb-out and climb modes leads to reduce mass of fuel burned correspondingly on an average 22%, 22% and 25%, fig.2.

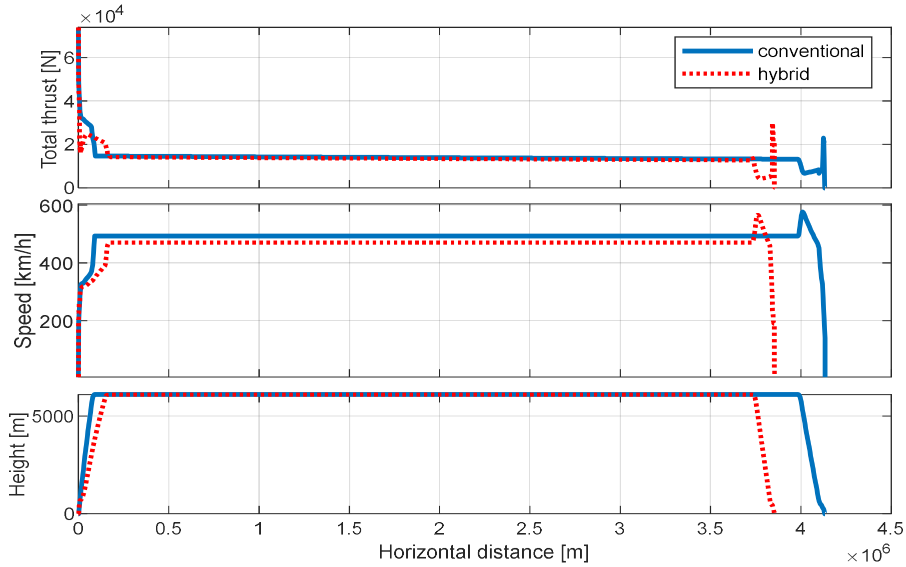

Fig.2. Comparison of flight profiles of an aircraft with a conventional and hybrid power plant: *a* – thrust produced with two engines; *b* – true flight speed; *c*– geometric flight height

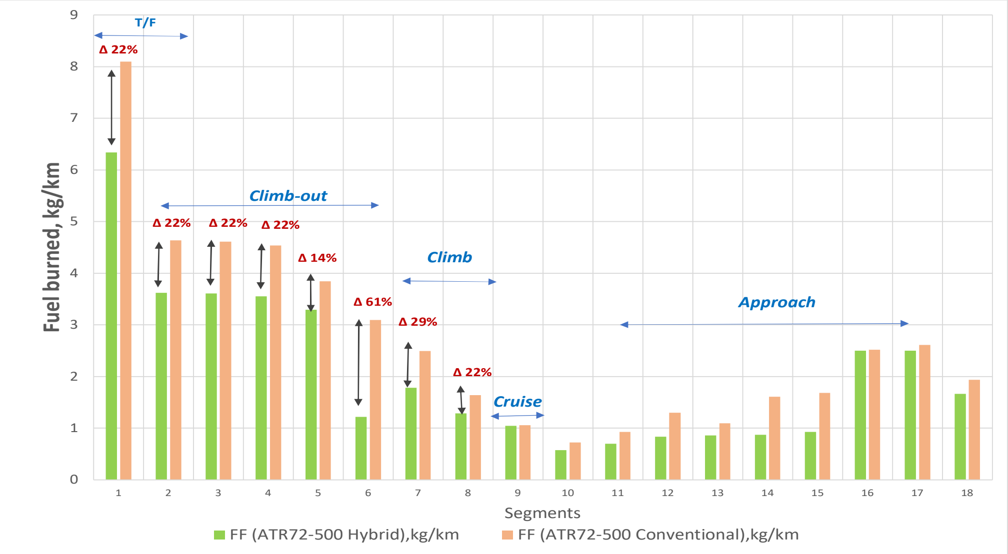

Fig.3. The mass of fuel burned calculated by PolEmiCa for each segment of flight profile for conventional and hybrid AT76

The same trends are found for emissions mass: CO_2 reduction was achieved on an average 24% at take-off and climb-out modes, 28% at climb mode; NOx reduction – on an average 40% at take-off mode, 45 % - climb-out and 43% - at climb mode, fig.4, 5.

The electric motors in the hybrid PS were used during the first 30 minutes of the flight. That made it possible to use a gas turbine engine with less power, since the most thrust is needed for the run-off, climb-out and climb, that reduce the fuel consumption and gaseous emissions.

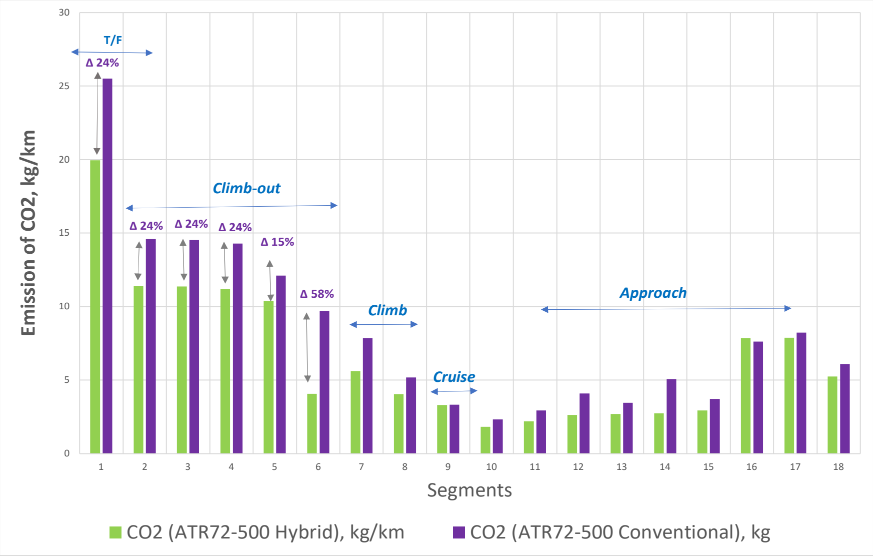

Fig.4. The mass of CO_2 emissions calculated by PolEmiCa for each segment of flight profile for conventional and hybrid AT76

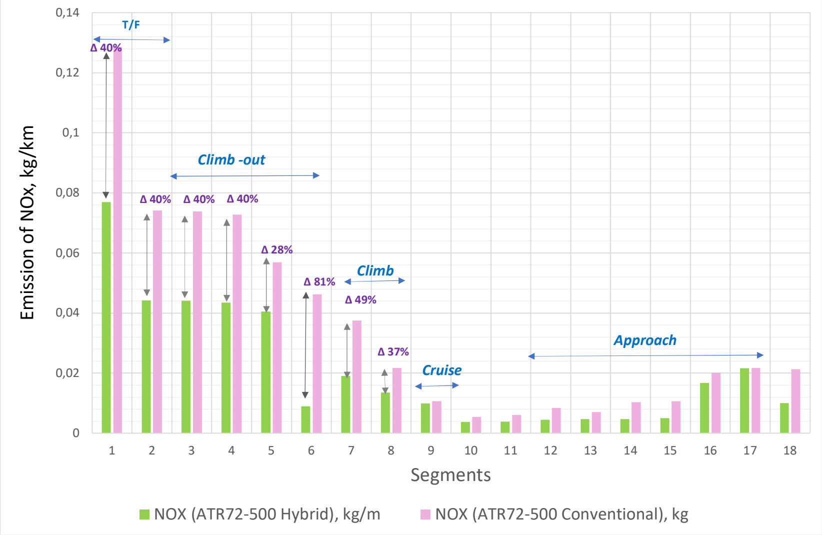

Fig.5. The mass of NOx emissions calculated by PolEmiCa for each segment of flight profile for conventional and hybrid AT76

5. REFERENCE AIRCRFT EMISSION MODEL FOR THE SUPERSONIC AIRCRAFT

One of the task of SeNeCa project to perform local air quality tasks for designed SST aircraft. For this purpose, the results of Environment Impact Assessment at Dulles International Airport (DIA) for Concorde were used as reference case.

5.1 Concorde Air Quality Monitoring and Analysis Program at US Airports

The experimental investigation was organized at DIA by FAA to test supersonic airplane CONCORD for compliance to air quality requirements as part of Environment Impact Assessment. Single-event measurements were used to define the Concorde influence area referred to in Fig.6, and to provide the detailed data for background - pollution analysis. The measurement procedure was to place the monitoring stations downwind of the Concorde movement path and measure the dispersion of the emission plume as it was transported by the wind over these stations. Major emphasis was placed upon monitoring the jet exhaust emissions from a **taxiing** and **taking off aircraft**. *Carbon monoxide (CO)* was the "tracer" measured for taxi and engine start idle emissions. *Nitrogen oxides* (*NOx)* was the "tracer" for take-off emissions. Vertical pollution measurements were made at five elevations on three vertical towers [12].

The air quality data consists of the following data sets:

- "Single Event" aircraft CO emissions during taxi (*St.№4, St.№5, St.№10, St.№11*)
- "Single Event" aircraft NOx emissions during take-off (*St.№12, St.№13, St.№14*)
- Multipoint three-tower measurements of CO emissions for taxi (*St.№20T, St.№21T, St.№22T, St.№27T, St.№28TT, St.№29TT, St.№30TT, St.№31TT*). The locations of the monitoring sites at the airport are shown in Fig. 6.

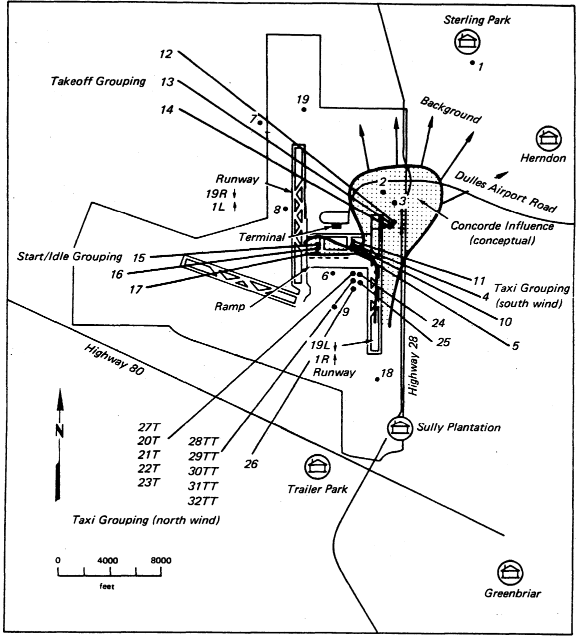

Fig. 6: Air monitoring sites at DIA

5.1.1 Taxi measurement at DIA

Comparison modelling and measurement results for taxing conditions

First of all, the parameters of the exhaust gases jet (Archimedes number Ar0, height ΔHa and longitudinal coordinate Xa of buoyancy effect, vertical σ_z and horizontal dispersion σ_x, σ_y) were estimated by PolEmiCa for Concord and B707 under taxing conditions, table.1.

Table 1

Parameters of exhaust gases jet for B707 and Concorde calculated by PolEmiCa for taxing conditions

AF	Mode	Buoyancy effect of jet			Dispersion parameters			Dispersion by AVAP	
		Ar0	H, m	Xa, m	бx	бy	бz	бy	бz
B707	TX	0,0004	2,10	69,89	5,55	19,4	5,54	22,46	3,26
Concorde	TX	0,0003	6,9	147,0	7,97	22,1	8,04	-	-

PolEmiCa includes the jet parameters influence on concentration distribution in the plume.

Modelled results of peak instantaneous concentration CO from one engine of B707 (fig.7) at height 14 feet are strong correlated with ground measurement (at the same height) at three stations №4, №5, №11 correspondingly, fig.9. Modelled results of peak instantaneous concentration CO from one engine of Concord (fig.8) at height 14 feet are strong correlated with ground measurement (at the same height) at three stations №4, №5, №11 fig.9.

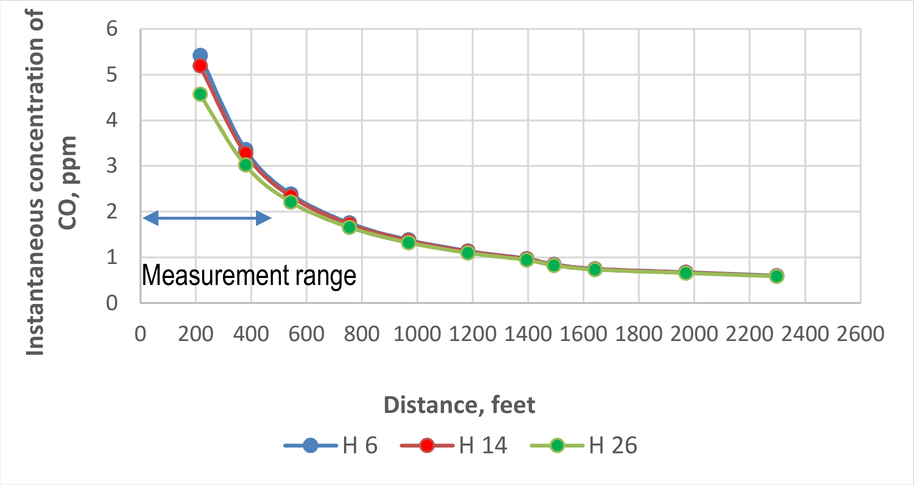

Fig.7. Modelled peak instantaneous concentration of CO from one engine of B707 at height 14 feet for taxi conditions

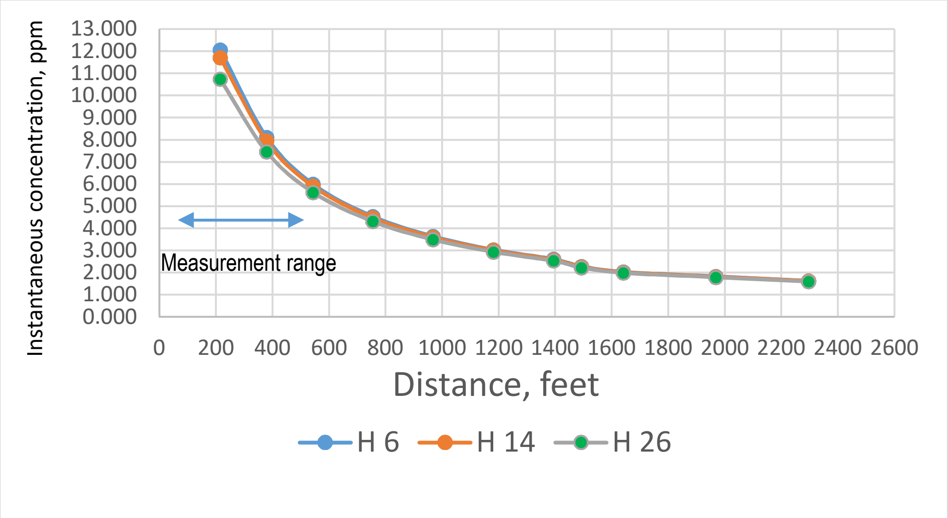

Fig.8 Modelled peak instantaneous concentration of CO from each engine of Concord at height 14 feet for taxi conditions

The peak CO concentration for Concorde is 2,25 times higher than the average concentration of B707 monitored at a location 200 ft downwind from taxing aircraft. Emissions from Concorde (and other airplanes) disperse to background levels before they reach the terminal (2300 feet from the ramp taxiway). The observe trends can be explained by influence the strong buoyancy effect (H), which diluted air contaminants until background values inside the airport area.

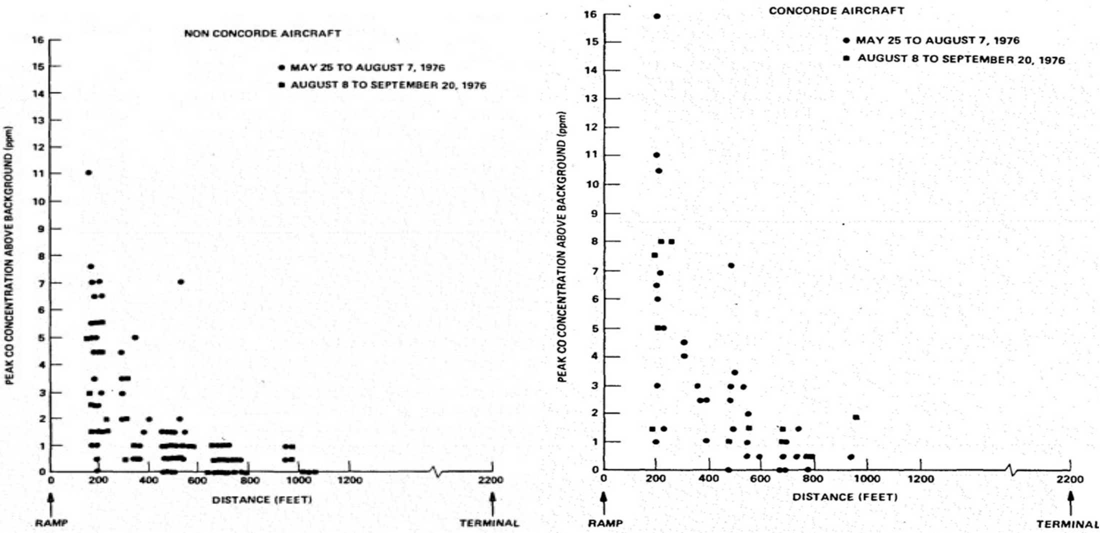

Fig.9 Measured peak instantaneous concentration of CO from each engine of B707 and Concord at height 14 feet for taxi conditions

5.1.2 Take-off measurement at DIA

Take-off NOx emissions were measured at the surface level at sites №12, №13, №14 are approximately 1000 feet south of the north end “19L” of the east runway. NOx measurements were taken at the three downwind locations to detect plume concentration from aircraft under acceleration and take-off conditions and measure the dispersion of the emissions plume as it was transported by wind and atmospheric turbulence over these stations. Characteristic traces of NOx measurement versus time are shown fig.10, which demonstrates detection three peaks of instantaneous concentration of NOx from aircraft engines per 1 minute [13]. Measurement results of NOx peak instantaneous concentration from Concord and non-Concord aircraft are plotted on the fig.10. Measurement data were collected for different wind direction (230^0 - 280^0) and wind velocity 6 m/s.

Due to measurement scenario conditions the modelling of instantaneous NOx concentration has been conducted by PolEmiCa. First of all, the parameters of the exhaust gases jet (Archimedes number Ar0, height ΔHa and longitudinal coordinate *X*a of buoyancy effect, jet penetration length Xj, vertical σ_z and horizontal dispersion σ_x, σ_y) were estimated by PolEmiCa for Concord and B707 under take-off conditions, table 2. So, PolEmiCa includes the jet influence on concentration distribution in the plume.

Modelled results of peak instantaneous concentration NOx of take -off Concorde for wind direction 230^0 at height 14 feet are strong correlated with ground measurement (at the same height) at three stations №14, №13, №12 [18] correspondingly, fig.10 and table 3.

The same trend was found for B707, the modelled results of peak instantaneous concentration NOx of take -off B707 for wind direction 230^0 at height 14 feet (correspondingly table 4) are in good agreement with ground measurement (at the same height) at three stations №14, №13, №12, fig.10 (***non Concord***).

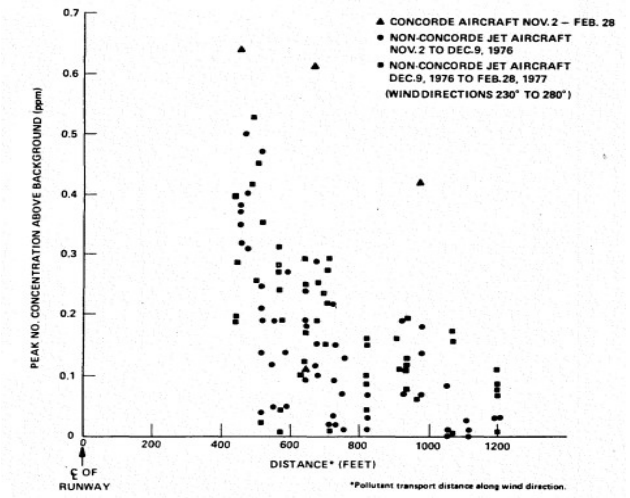

Fig.10 Instantaneous concentration of NOx during take-off

Table 2

Parameters of exhaust gases jet for B707 and Concorde calculated by PolEmiCa for take-off conditions and wind direction (230°)

AF	**Engine**	**Mode**	**Buoyancy effect of jet**			**Jet length and radius expansion,m**			**Dispersion parameters**		
			Ar0	**H, m**	**Xa, m**	**Xj**	**Sm**	**Rm**	**Ϭx**	**Ϭy**	**Ϭz**
B707	JT3D-3B	TF	0,00005	2,53	271,5	144,87	190,84	8,97	8,80	25,44	8,38
Concorde	Olympus-593-610	TF	0,00006	8,34	330,0	239,71	309,11	10,98	10,71	26,95	10,51

Table 3

Modelled results of peak instantaneous concentration NOx by PolEmiCa in plume from one engine at take -off Concorde (WD=230°)

station	**Distance**	**H 6**	**H 14**	**H 26**
14	**450**	**0,62**	**0,61**	**0,59**
13	**635**	**0,50**	**0,50**	**0,48**
12	**929**	**0,39**	**0,38**	**0,38**

Table 4

Modelled results of peak instantaneous concentration NOx by PolEmiCa in plume from one engine at take -off B707 (WD=230°)

station	**Distance**	**H 6**	**H 14**	**H 26**
14	**450**	0,23	0,23	0,22
13	**635**	0,18	0,18	0,17
12	**929**	0,14	0,13	0,13

Analysis of measured and modelling concentration shows, that Concorde emissions are higher than the concentrations from B707, but due to effects of the jet dynamic effects air pollutants are strongly and quickly diluted until background levels.

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Conclusions:

1. Analysis of the studies has demonstrated fuel burn assessment of the individual technologies for different aircraft groups. In general, rolled-up engine technologies contribute larger fuel burn benefits that aerodynamic and structural technologies only.
2. Comparison of modeling results for the AT76 type aircraft with conventional and hybrid power plants for the throughout flight profile (EFACA project) concludes, that application of electric motors at take-off, climb-out and climb modes leads to reduce mass of fuel burned correspondingly on an average 22%, 22% and 25%. The same trends are found for emissions mass: CO_2 reduction was achieved on an average 24% at take-off and climb-out modes, 28% at climb mode; NOx reduction – on an average 40% at take-off mode, 45 % - climb-out and 43% - at climb mode.
3. The validation studies on the basis of measurement campaigns at DIA shows that both the initial plume rise and the jet wake dispersion of air effluents have important effects on pollutant concentration estimates for receptor located within a kilometer of the source pathway. The obtained results will be used for local air quality studies of SST aircraft of SeNeCa project.

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