Methods to Assess Aircraft Engine Emissions in Flight

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ABSTRACT

The pollution from airtraffic and its environmental aspect has become an outstanding objective of international investigation during the recent years not only in the vicinity of airports but even more within the range of cruise altitudes. The products of ideal combustion like carbondioxide (CO_2), watervapor (H_2O) and sulphurdioxide (SO_2) are directly coupled with the amount of fuel burnt, whereas the emission of other trace species like nitrous oxides (NO_x), carbonmonoxide (CO) and unburned hydrocarbons(UHC) depends on the the combustion process itself, which is controlled by the engine load condition. To assess aircraft engine emission in flight three different subjects have to be combined. The one is the thrust demand of an aircraft given by its actual flight performance, the second is the subsequent thermodynamical status of the engine to deliver this thrust and third its effect on the production of emissions by the combustor. All three aspects have been looked at to form a modeling procedure to calculate engine emissions. A short overlook will be given on an aircraft flight performance model as well as on the thermodynamic model to characterize an engine. Both have been used to balance aircraft and engine performance for a given flight situation. From this parameters controlling the combustion process will be given, such as combustor inlet temperature, inlet pressure, air- and fuel mass flow. In more detail it is shown, which methods have been developed to correlate engine performance and emission production and how these methods and their application will effect the results. Due to the complexity of a combustion process all methods employed are semi-empirical and will be based on sea level static test data on engine emissions as published by the ICAO. Within the course of the studies a simplified method has been developed, which makes it possible to correlate NO_x emissions, fuel flow and varying engine inlet conditions. The advantage of such a method will be first of all its simplicity and its possibility to bypass normally sensitive and competitive engine data.

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NOMENCLATURE

C_D, C_L: drag and lift coefficient
C_{D_0}, C_{L_0}: minimum drag and corresponding lift
$C_{D_{(L/D)_{max}}}, C_{L_{(L/D)_{max}}}$: coeff. at best aerody. eff.
$corr$: corrected values for ambient conditions
δ: pressure correction factor
FC: fuel consumption
FR: flight range
EI: emission index, emissions[g]/fuel burnt[kg]
F_H: humidity factor
GS: ground speed
GW_1: gross weight at beginning of cruise/segment
g: gravity$=9.81 m/s^2$
IAS: indicated airspeed
L/D: lift over drag
SFC: specific fuel consumption
T_0, p_0: ambient static temperature and pressure
T_{t1}, p_{t1}: engine inlet total temp. and pressure
T_{t3}, p_{t3}: combustor inlet total temp. and pressure
T_{t4}, p_{t4}: combustor outlet total temp. and pressure
$T_{\lambda=1}$: stoichiometric flame temperature
$T_m = \frac{1}{2} \cdot (T_{t3} + T_{t4})$
Θ: temperature correction factor
Θ_C: combustor loading parameter
$t_E, t_{E,ref}$: evaporation time, reference evapo. time
w: weight flow[kg/s]

1. INTRODUCTION

Because airtraffic has been increasing substantially during the last decades the environmental aspect has become an important objective within the atmospheric sciences. Wether or not pollutants from airtraffic may disturb - among others - the climatic balance above natural variability is still an ongoing investigation. Research programs have been established dealing with the impact of combustion products out of aircraft engines directly injected into sensitive areas within and above the tropopause at cruising altitudes. Therefore one step has been to establish global inventories of gaseous emissions from the airtraffic.

These inventories then will be used as an input for computer codes modelling the physics and chemistry of the atmosphere. Concerning fossile fuels and their combustion products the gaseous emissions like CO_2, H_2O and SO_2 are directly coupled with the amount of fuel burnt, whereas the emission of other trace species like NO_x, CO and UHC depends on the individual load condition of a specific engine and will be controlled by the internal combustion process itself. Thus two questions have to be answered in order to assess aircraft engine emissions: first of all, what is the amount of fuel for a specific aircraft engine combination along its flight mission, and second what are the associated emissions? Within this paper methods will be described and evaluated concerning both of these questions but preferably with emphasize on the second one.

2. FLIGHT PERFORMANCE

The given flight path and the payload range diagram are responsible for the the power demand of the aircraft. During steady cruising phases the thrust demand is only connected with the actual aircraft weight and the actual (L/D)-value. Additional thrust must be delivered by the engines in cases of take off, climb and/or acceleration modes.

Describing the aerodynamical behaviour of the whole airplane an overall lift over drag polar is used. In this polar compressible effects are omitted. Due to asymmetric airfoils a parabolic polar curve is assumed which is asymmetric too. This means, the lift coefficient at minimum drag is not neglible ($C_{A_0} \neq 0$), as denoted in Figure 1. Best aerodynamic efficiency can be found in the single point $(L/D)_{max}$, (Figure 1) respectively as quotient between $C_{D_{(L/D)_{max}}}$ and $C_{L_{(L/D)_{max}}}$. In Table 1 an overview of these important parameters can be found, splittet up into different aircraft types.

Using an asymmetric polar describing the aerodynamic relationship between lift and drag, two characteristic values are needed generating these polar: the vertex of the polar (C_{D_0}, C_{L_0}) and the point of best aerodynamic efficiency $(C_{D_{(L/D)_{max}}}, C_{L_{(L/D)_{max}}})$. Of course, obtaining the lift coefficient with respect to the aircraft gross weight the wing area had to be known as well as the flight altitude and the velocity. Having all main charcteristic values, every other drag coefficient can be evaluated via

$$C_L = C_{L_0} + (C_{L_{(L/D)_{max}}} - C_{L_0}) \cdot \sqrt{\frac{C_D - C_{D_0}}{C_{D_{(L/D)_{max}}} - C_{D_0}}} \tag{2.1}$$

with

$$C_{L_0} = C_{L_{(L/D)_{max}}} \cdot \left[1 - 2 \cdot \left(1 - \frac{C_{D_0}}{C_{D_{(L/D)_{max}}}}\right)\right] \tag{2.2}$$

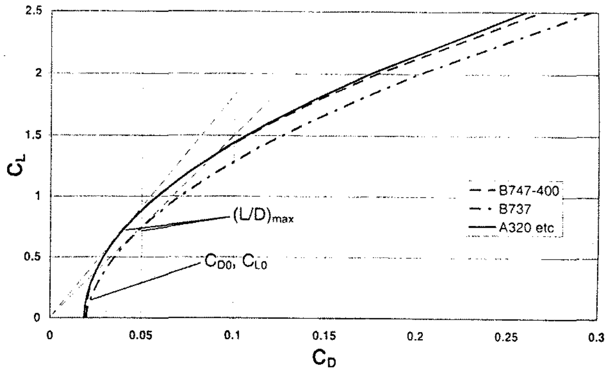

Figure 1: Used overall parabolic polar

Airplane	C_{D_0}	C_D at $(\frac{L}{D})_{max}$	C_L at $(\frac{L}{D})_{max}$	Wing area $[m^2]$
A 320	0.0185	0.0385	0.7	122.4
B 737	0.0185	0.047	0.7	105.4
B 747	0.0185	0.038	0.7	511

Table 1: Used aircraft's characteristic values in the flight performance program

To fulfil practical constrains concerning typical time margins for each flight phase the power setting of the engine and the overall polar respectively, the following assumptions have been made. Adapting the aircraft engine performance take off times less than 40 seconds are to be reached. The time reaching 'top of climb' should be in the range of 20 minutes. Typical descent times are approximately 30 minutes flown at engine idle conditions.

The climb phase is divided into three sections: Until 10000ft of altitude the indicated airspeed is kept constant at IAS=250kts, leading to a continuous increase in true airspeed. Between 10000ft and flight level FL=290 (29000ft) the IAS is set to IAS=300kt. Beyond this point the climbing phase is continued keeping the Mach-number constant.

The fuel consumption during cruise mode (FC) for a given flight range (FR) is calculated with the Breguet-formula including ground speed (GS) and the gross-weight at the beginning point of cruise (GW_1):

$$FR = \frac{GS \cdot (L/D)}{SFC \cdot g} \cdot ln \left[\frac{1}{1 - \frac{FC}{GW_1}} \right] \qquad (2.3)$$

Certainly this formula can be obtainted by keeping the specific fuel consumption the (L/D)-value and GS constant during the whole cruise. These assumptions may be rough for a long-range-flight.

To examine the influence of the nonconstant L/D- and SFC-values on the results evaluated with the Breguet-formula the cruise range is devided into several segments having the same length. The fuel consumption along every segment is determined with the Breguet-formula using the L/D- and SFC-values at the beginning of each segment. Figure 2 shows the change of total cruise fuel for a 8000km-mission calculated with 1 to 20 segments with the 20 segments value set to 100%.

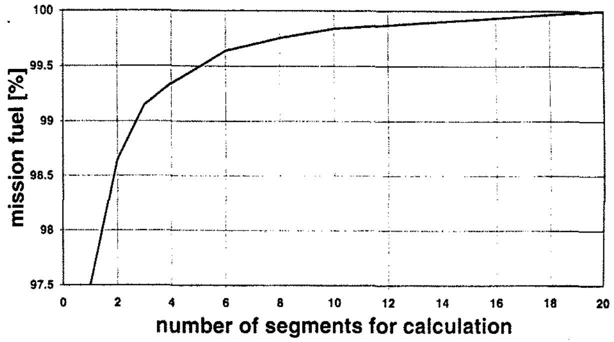

Figure 2: Influence on fuel splitting a 8000km cruise into different number of segments

Further investigations with mission ranges of 2000km and 12000km show a nearly linear percentage increase of the calculated fuel amount with increasing mission range (20 segments) compared to a mission calculated with two segments, Figure 3.

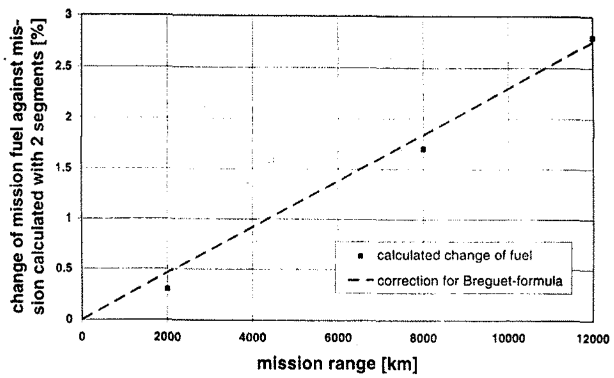

Figure 3: Change of mission fuel against mission calculated with 2 segments

The function for the correction of the total mission fuel shown in Figure 3 is:

$$\text{percentage change of fuel} = 2.3 \cdot 10^{-4} \cdot \text{cruise range(km)} \qquad (2.4)$$

This function is used to correct the total fuel of a mission calculated with the Breguet-formula and two cruise segments.

3. ENGINE MODEL

After evaluating the necessary thrust demand of the aircraft with the help of the flight performance model, the engines had to fulfil these thrust requirements. Looking at the whole flight path it is essential to develop an engine performance model including design and off-design features of a conventional bypass engine. To predict all aircraft emissions during the whole flight phase not only the fuel flow at any operating point has to be known. The production of thermal NO_x, CO and unburned hydrocarbons also depends on the combustor inlet conditions, mainly inlet temperature and pressure. Regarding this second issue the development of an engine performance program to predict the design and off-design behaviour is also necessary.

Due to a lack of detailed engine performance data obtained from the aircarft/engine manufactures the engine model has to be as accurate as possible knowing only a few main engine design parameters. Having the most available data at the 100% thrust point at SLS (sea level static) conditions, these single point is choosen to be the design point of the engine. Commonly, the available design parameters (from ICAO [3], Jane's [4], Lufthansa [5]) can be mentioned as shown in Table 2.

available	assumed
thrust, fuel and air mass flow, bypass ratio, lower heat value, overall pressure ratio, turbine entry temperature (TET)*, fan pressure ratio*, engine press. ratio*	amount of cooling air, pressure ratio resp. pressure loss of each component, polytropic efficiencies, spec. heats for compression and expansion

Table 2: Available and assumed engine parameters for the 100% thrust point at sea level static conditions (=design-point of the engine). Values marked with an $\star$ are not always published.

Furthermore, this table includes additional engine parameters which have to be assumed and fitted for the design point.

The developed engine performance model is briefly described in [2], derived from [9], [11]. Physicaly the model is based on the following assumptions and relations.

Fulfilling the power equations of the high pressure and the low pressure spool the enthalpie delivered by the turbine must be matched with the compressor demands, taking into account the effect of mechanical losses. No power off take is assumed. The bleed air is substituted by the fuel flow in the combustion chamber.

The pressure balance through the engine must be reached. Multiplying all discrete pressure ratios of each engine components the nozzle pressure ratio of the core must be obtained.

The thermodynamical exit conditions of each component are the inlet conditions of the next one, except mixing of bypass or cooling air will occur.

The continuity of the mass flow in every engine section has to be considered.

During engine operating the nozzles are responsible for the absolut amount of total air mass flow passing the engine. The core nozzle also fixes the turbine operating points for 'choking' conditions. This means, no change in the high pressure and low pressure turbine (HPT,LPT) will be noticed while operating at nozzle pressure ratios greater than the critical value. Only at low altitude the core nozzle expands 'unchoked'. At the 100% thrust point (SLS) the engine pressure ratio (EPR) of a civil bypass engine is about EPR≈1.5 and in this case equal to the core nozzle pressure ratio, showing that the nozzle is 'unchoked' even at this high power setting of the engine. The bypass nozzle is unchoked as well (SLS).

Effects of turbine-nozzle interferences are used for simplifying the calculation procedure in the program. For example, the pressure ratio of the LP-turbine can be obtained via two separate equations. The first relationship corresponds to the compressor enthalpy demands (from the power equation) and the second with the nozzle-LPT-matching. An internal loop in the computer program has to balance both LPT-values to fulfil the given constraints.

Running in the off-design mode some reduction in the efficiencies of the turbocomponents will arise. In general the design point is not necessarily connected with best component isentropic or polytropic efficiency. One possible reason for this behaviour is to ensure adequate surge margin limits. On the other hand, optimal turbine and compressor efficiencies should be in the range of typical cruising engine operations. In the used loss model the decrease in polytropic efficiency is connected with the reduced mass flow through the engine. Best efficiencies are at 92.5% max. reduced mass flow within typical cruising conditions.

Loss increases drastically for the fan and booster running near engine-idle. No change in efficiency for the HPT is assumed. Due to adjustable stator vanes the loss production for the HPC is less then for the other compressors.

Figure 4 shows good agreement between measured SFC-values from ICAO data sheets [3] and predicted values under SLS engine running conditions.

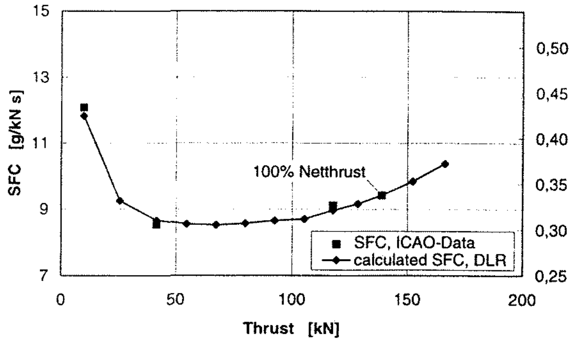

Figure 4: Comparison of measured SFC-values from ICAO [3] and predicted values under SLS engine running conditions for the CFM56-5C2

For the same engine calculated SFC-values at a typical cruising altitude (Flight Level 350) can be found in Figure 5.

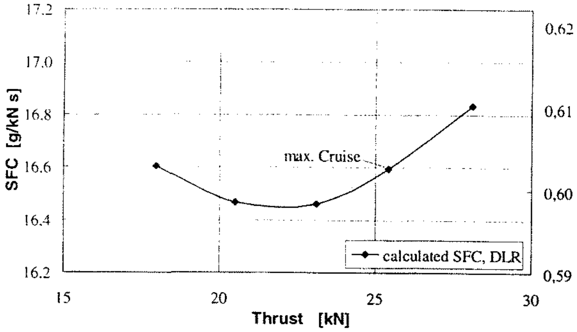

Figure 5: Calculated SFC-values at FL=350 for the CFM56-5C2

4. EMISSION-CALCULATION

Concerning the certification of a turbofan or turbojet engine the manufactures are obliged to measure the emissions of the engines under sea level static conditions. These measurements for different power settings of the engines built up the ICAO database (ICAO Exhaust Emission Data Bank [3]).

Up to now, measured values under flight conditions are rarely published except inflight measurement due to actual research investigations. Taken this into account, emission-values for realistic flight phases have to be assessed using calculated engine parameters and semiempirical correlations. Looking at several existing correlation methods three main categories can be classified: The first category are procedures which use the measured EI-values at sea level (from ICAO) as a reference and try to find the actual flight emission index with the help of formulas based on kinetic relationships or on 'best fit' curves related to typical combustor inlet values (chapter 4.1). The second category can be named 'absolute'. In this correlations the amount of NO_x can be derived without having typical reference values at sea level using only combustor inlet and design parameters. Within this paper there will be no closer look to this kind of correlations. The third category can be summarized as the so called 'fuel flow methods', see chapter 4.2. In this case only available engine monitored fuel flow and ambient flight conditions as well as measured EI-values at sea level are necessary, for instance informations from the ICAO engine emission-datasheet.

4.1 'Relative' correlations

Considering the formation of emissions within a combustor a model based on two characteristic times may be used. On the one hand there is the reaction time needed for a special chemical reaction and on the other hand there is the residence time of the reaction partners within the pressurized and heated volume. The ratio out of these times mainly controls the formation or the reduction of special combustion products such as NO_x, CO or UHC. The NO_x formation is proportional to the residence time divided by the reaction time. The CO and the UHC formation shows quite the opposite behaviour.

4.1.1 Nitrous oxides

Based on this model of characteristic times [6] the following equation to correlate the NO_x emission index at inflight conditions $(EINO_x)_F$ with that of a measured reference value $(EINO_x)_{SL}$ at sea level static conditions (SLS) can be established:

$$(EINO_x)_F = (EINO_x)_{SL} \ \times$$

$$\frac{e^{\left(\frac{67500}{T_{\lambda=1}}\right)_{SL}}}{e^{\left(\frac{67500}{T_{\lambda=1}}\right)_F}} \cdot \frac{(p_{t3})_F}{(p_{t3})_{SL}} \cdot \frac{(w_{air})_{SL}}{(w_{air})_F} \cdot \frac{(T_{t3})_{SL}}{(T_{t3})_F} \cdot F_H \quad (4.1)$$

With the stoichiometric flame temperatue $T_{\lambda=1}$, the combustor inlet pressure p_3 and temperature T_3 and the air core mass flow w_{air}.

SL denotes sea level, F denotes flight conditions. The humidity factor F_H can be found in (4.24). $T_{\lambda=1}$ can be found as an approach from values given by Zahavi [12]:

$$T_{\lambda=1} = 2281K \cdot (p_{t3}^{0.009375} + 0.000178 \cdot p_{t3}^{0.055} \times$$

$$(T_{t3} - 298)) \quad [p_{t3}] \text{ in bar}, \ [T_{t3}] \text{in K} \quad (4.2)$$

These example of a 'relative' correlation needs engine data at sea level (SLS) and the measured EI-values. In principle there are two different ways to handle equations like (4.1). First of all, the EI-value can be treated as a fixed reference (for instance at 100% thrust). Then of course all combustor inlet parameters at sea level must be refered to this single point. A second possibility is the use of the reference EI-value at sea level as a 'gliding' non fixed reference point. Then all sea level reference values like $(T_{\lambda=1})_{SL}$, $(w_{air})_{SL}$, $(p_{t3})_{SL}$ and $(EINO_x)_{SL}$ are needed as functions of the combustor inlet temperatures at sea level conditions, and will be correlated at a common value related to this temperature.

4.1.2 Carbonmonoxide

For carbonmonoxide following 'relative' equation can be used, showing at least the difference in the quotient of the characteristic times:

$$(EICO)_F = (EICO)_{SL} \ \times$$

$$\frac{e^{\left(\frac{5380}{T_m}\right)_F}}{e^{\left(\frac{5380}{T_m}\right)_{SL}}} \cdot \frac{(p_{t3})_{SL}}{(p_{t3})_F} \cdot \frac{(w_{air})_F}{(w_{air})_{SL}} \cdot \frac{(T_{t3})_F}{(T_{t3})_{SL}} \quad (4.3)$$

with $T_m = 0.5(T_{t3} + T_{t4})$.

CO and UHC are interim products during the combustion of hydrocarbons and air. The idea of the following developed method to calculate these emissions is to correlate them with the combustion efficiency η_C which is a function of the combustor loading parameter Θ_C [7].

$$\Theta_C = \frac{V_C \cdot p_{t3}^n \cdot e^{(\frac{T_{t3}}{b})}}{w_{air}} \tag{4.4}$$

The volume of the combustor V_C is constant and the CO und UHC production is conversely proportional to Θ_C so one gets

$$EICO,\ EIUHC = F(\frac{V_C}{\Theta_C}) = F\left[\frac{w_{air}}{p_{t3}^n \cdot e^{(\frac{T_{t3}}{b})}}\right] \tag{4.5}$$

with n ~ 1.75..1.8 and b ~ 300 K.

The function F [7] has to be determined with known data for example from ICAO data sheets [3] and the engine model described above. Figure 6 shows the function F for the PW 305 engine measured within the national research program 'Pollution from Air-traffic'. The measurements took place in the altitude test facility at the University of Stuttgart as share of MTU.

$$EICO = -0.751 + 590.1 \cdot (\frac{V_C}{\Theta_C}) \tag{4.6}$$

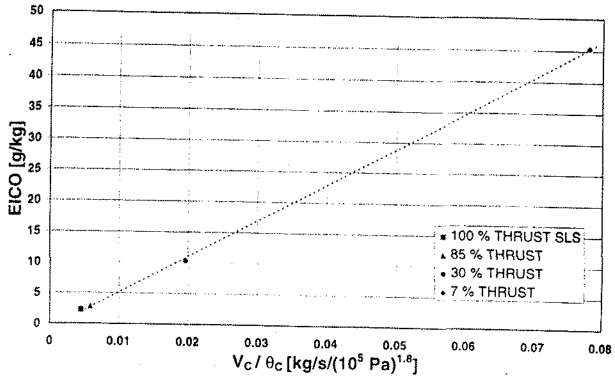

Figure 6: EICO versus $\frac{V_C}{\Theta_C}$ for the PW305

Due to the wide variety of T_{t3} und p_{t3} during engine operation conditions especially at very high cruise altitudes a correction concerning the evaporation time t_E based on the changing Sauter mean diameter in comparison to a reference value is developed, leading to:

$$EICO = \left[-0.751 + 590.1 \cdot (\frac{V_C}{\Theta_C})\right] \cdot \left[\frac{t_E}{t_{E,ref}}\right]^{0.4} \tag{4.7}$$

A comparison between measured and with formula (4.7) calculated emission indices for the PW 305 at altitudes from 0 to 50000 ft is shown in figure 7.

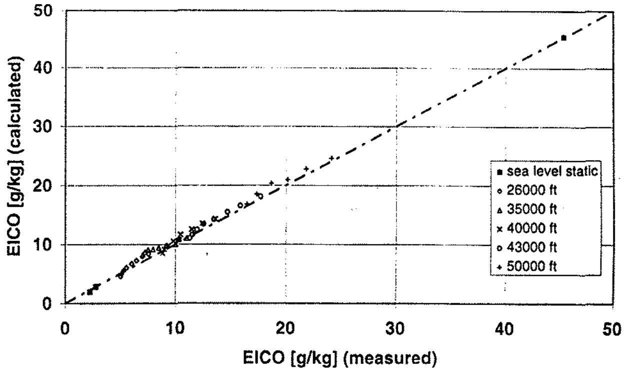

Figure 7: Calculated EICO versus measured EICO for the PW305

For the EIUHC a similar function giving not as good results as the CO-correlation can be developed for the PW305. Figure 8 shows, especially at FL=350 smaller predicted values than the measured ones.

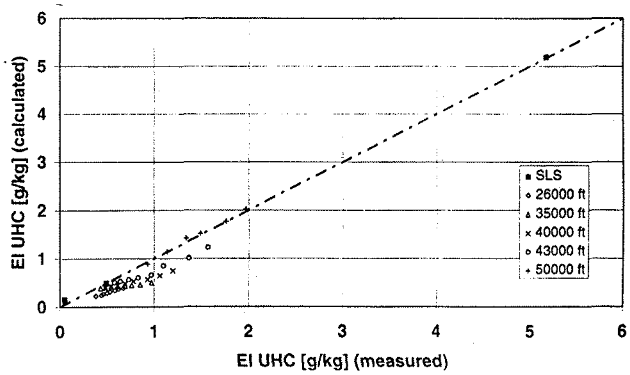

Figure 8: Calculated EIUHC versus measured EIUHC for the PW305

4.2 Fuel flow methods

All methods to correlate engine emissions for different operating conditions discussed so far will require engine data, which are normally sensitive and competitive from an engine manufacturer's point of view. The more complex a formular is to describe the physical and chemical reactions the more details of a combustor must be known with respect not only to its design but also to some extended test data. Therefore it might be usefull to look for some methods to simplify a correlation as much as applicable for a certain purpose.

As an example Figure 9 shows the results from one of the correlation models (eqn. 4.1) in combination with a thermodynamical engine modelling. The results reveal a clear spread of functions according to selected different atmospheric and flight phase conditions. As a comparison the ICAO LTO cycle test data are specially marked.

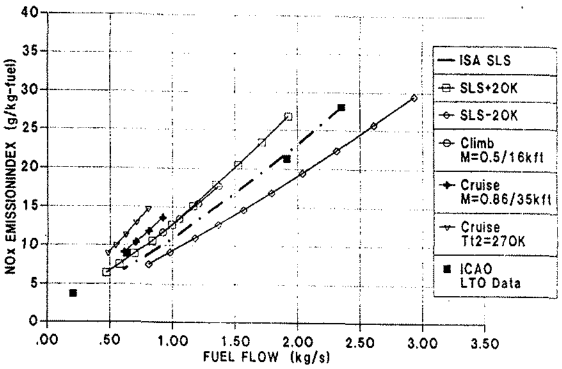

Figure 9: NO_x emission index versus fuel flow at different engine inlet conditions (CF6-80 type modelling)

The problem now is to find a possibilty for a reasonable correction so that from these different curves a single function can be achieved. A way to such a solution may be based on the following background.

An aircraft engine is mainly exposed to different conditions of total pressure and temperature at the air intake arising from ambient pressure and temperature depending on altitude and the flight velocity. Therefore the impact of these variable inlet conditions on the internal thermodynamical situation of an engine at a given power setting may be transferable by certain similarity rules. In engine testing for instance some corrections have to be made if the ambient atmospheric test conditions are different from the choosen reference standard conditions i. e. ISA (International Standard Atmosphere).

The factors used for these corrections are:

$$\delta = p_{t1}/p_0 \qquad p_0 = 101325 Pa \tag{4.8}$$

$$\Theta = T_{t1}/T_0 \qquad T_0 = 288.15 K \tag{4.9}$$

with p_{t1} [Pa] and T_{t1} [K] as the actual total pressure and total temperature at the engine air intake.

The corrections with respect to different inlet conditions can be deduced applying the following assumptions: the corrected data should reflect the equivalent operating point of the same engine at reference inlet conditions. This means that the core engine pressure ratio is assumed to be the same, because the engine is to run at the same corrected speed

$$n_{corr} = n/\sqrt{\Theta} \tag{4.10}$$

and the same corrected weight flow

$$w_{corr} = w \cdot \sqrt{\Theta}/\delta \tag{4.11}$$

therefore the following correction with respect to the combustor inlet pressure and temperature can be made

$$p_{t3,corr} = p_{t3}/\delta \tag{4.12}$$

$$T_{t3,corr} = T_{t3}/\Theta \tag{4.13}$$

Herein for the temperature correction the equivalence of the compressor efficiencies has to be maintained.

In order to correct the fuel flow with respect to different inlet conditions the following relation can be found

$$w_{fuel,corr} = \frac{w_{fuel}}{(\delta \cdot \sqrt{\Theta})} \tag{4.14}$$

by assuming that for similar engine cycle operating points with constant combustion efficiencies the added heat may be proportional to the airflow and the inlet air temperature using equations (4.9) and (4.11) for a correction.

As an example the effect of correcting the combustor inlet temperature and the fuel flow can be shown from the engine thermodynamic modelling of operating points at different ambient atmospheric conditions.

Figure 10 and Figure 11 show that the spread of curves from the actual values will already coincide with one function of corrected combustor inlet temperatur versus corrected fuel flow. Because combustor inlet temperature is one of the most important quantity to control the engine NO_x emission for a conventional combustor, at first it has been looked for a correction of the NO_x emission index versus the corrected combustor inlet temperature.

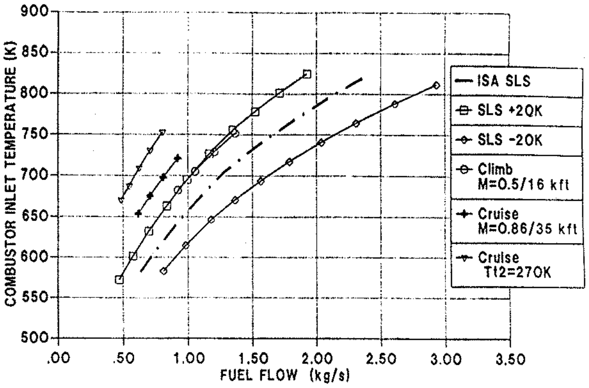

Figure 10: Combustor inlet temperature versus fuel flow

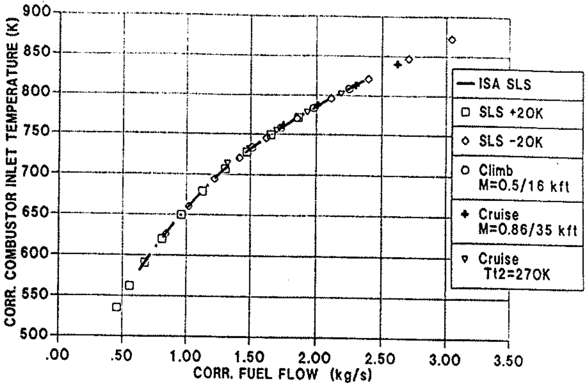

Figure 11: Corrected combustor inlet temperature versus corrected fuel flow (Reference inlet conditions: ISA, SLS)

To correct the NO_x emission index a formula can be deduced by the following considerations. If the combustor inlet temperature and pressure for corresponding operating points is a linear function of the respective reference operating point

$$T_{t3} = \Theta \cdot T_{t3,corr} \quad \text{from eqn.(4.13)} \tag{4.15}$$

$$p_{t3} = \delta \cdot p_{t3,corr} \quad \text{from eqn.(4.12)} \tag{4.16}$$

and if the NO_x emission index is a non-linear function of the combustor inlet temperature and the pressure respectively the following relation may be established

$$EINO_x \sim T_{t3}^a \sim \Theta^a \cdot T_{t3,corr}^a \tag{4.17}$$

$$EINO_x \sim p_{t3}^b \sim \delta^b \cdot p_{t3,corr}^b \tag{4.18}$$

For the corrected NO_x emission index $EINO_{x,corr}$ this must then be true as well, with Θ=1 and δ=1

$$EINO_{x,corr} \sim T_{t3,corr}^a \tag{4.19}$$

$$EINO_{x,corr} \sim p_{t3,corr}^b \tag{4.20}$$

Therefore the following ratio between corrected and actual NO_x emission index can be established

$$\frac{EINO_{x,corr}}{EINO_x} = \frac{1}{\Theta^a \cdot \delta^b} \tag{4.21}$$

By finding the values of the exponents a and b the spread of function of the actual NO_x emission index versus combustor inlet temperature (Figure 12) can be collected into one fit (Figure 13) if the above corrections are applied.

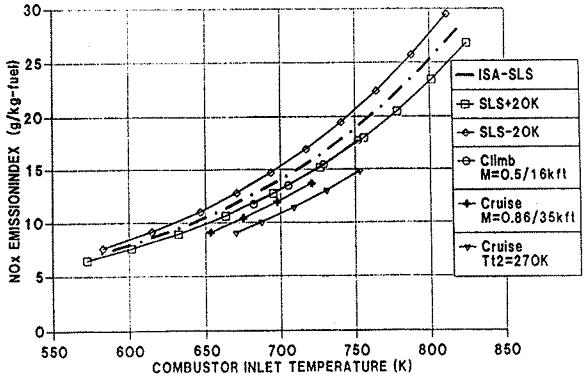

Figure 12: NO_x emission index versus combustor inlet temperature (CF6-80 type engine modelling)

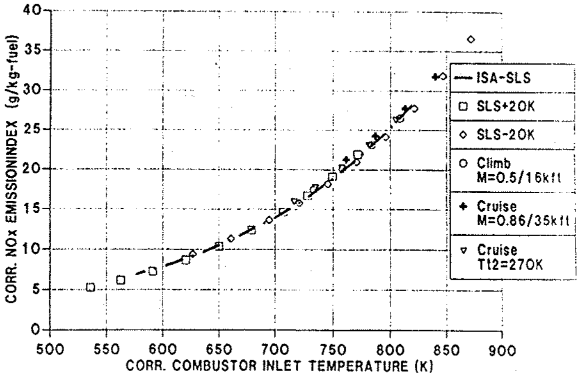

Figure 13: Corrected NO_x emission index versus corrected combustor inlet temperature (Reference inlet conditions: ISA, SLS)

To reach this correlation the following exponents have been found. For the inlet temperature correction a=3 and for the inlet pressure correction b=0.4 give the best fit. If the corrected NO_x emission index can be plotted as a function of the corrected combustor inlet temperature (Figure 13), then as a consequence out of the results shown in Figure 11 it can well be presented as a function of the corrected fuel flow.

Figure 14 shows this result and generally reveals the possibility to simplify NO_x emission index assesment for inflight engine operation by means of the actual fuel flow and an adequate correction with respect to the engine inlet total temperature and total pressure conditions.

A validation of this method could be demonstrated from real engine measurements in an altitude test chamber within the AERONOX program supported by the EC [1].

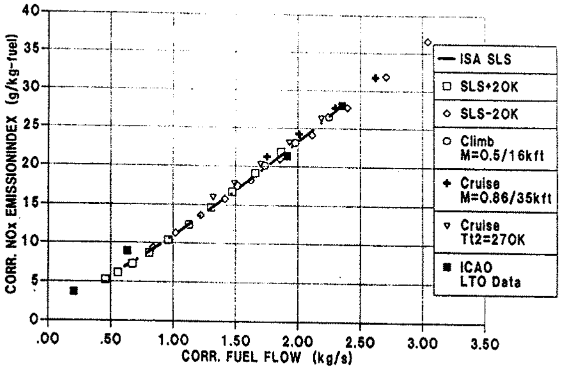

Figure 14: Corrected NO_x emission index versus corrected fuel flow (CF6-80 type engine modelling, ISA-SLS reference inlet conditions)

Figure 15 and 16 show the outcome of correcting the NO_x emission index and the fuel flow for a Rolls Royce RB211 type engine although the values a and b originally had been developed by modelling a General Electric CF6-80 type engine.

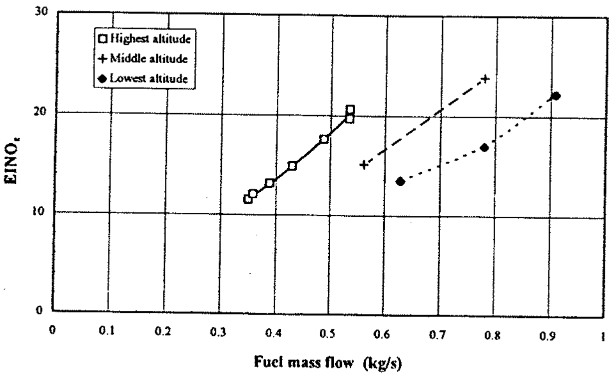

Figure 15: RB211 engine, $EINO_x$ versus fuel flow [1]

Within this excercise the measured values have been referred to the high altitude inlet conditions, that is, generally one is free to choose the level of reference inlet conditions.

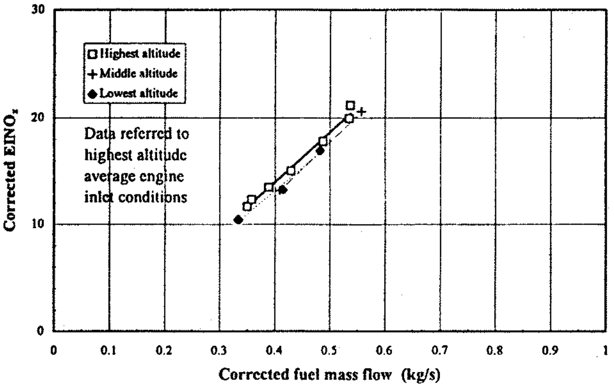

Figure 16: RB211 engine, corrected $EINO_x$ versus corrected fuel flow [1]

If in one case the function of the corrected NO_x emission index versus corrected fuel flow will be given, the following procedure to calculate the $EINO_x$ for any other operating point may be outlined as follows: correct the actual given fuel flow of the engine by

$$w_{fuel,corr} = w_{fuel}/(\delta \cdot \sqrt{\Theta}) \qquad (4.22)$$

with respect to the given reference inlet conditions and get the corrected NO_x emission index $EINO_{x,corr}$ from the given function. The actual NO_x emission index than can be evaluated by recorrecting

$$EINO_x = EINO_{x,corr} \cdot \Theta^3 \cdot \delta^{0.4} \cdot F_H \qquad (4.23)$$

Here a factor F_H to account for an additional effect of any change in ambient absolute humidity should be put on. Within the here deduced methology this had not jet been addressed, because this is not normally considered to be a factor influencing an engine operating point itself. This factor might be therefore introduced in behind and will be expressed as [8]:

$$F_H = EXP\left[\frac{6.29 - e^{-0.000143(Alt[ft]-12900)}}{53.2}\right] \qquad (4.24)$$

A method to calculate the amount of CO and UHC may be developed connecting the fuel flow and the emission index similar to the NO_x fuel flow. $EICO$ versus fuel flow for the PW 305 shows a functional behaviour for all measured altitudes, Figure 17.

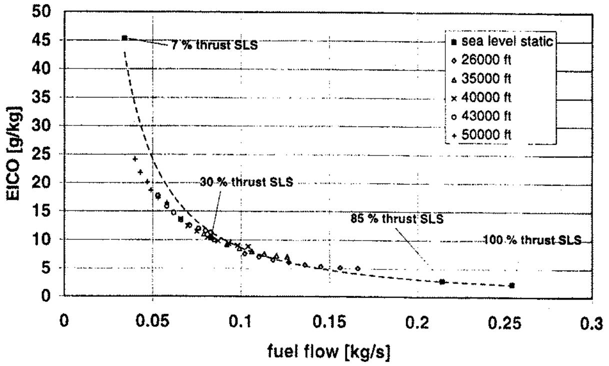

Figure 17: Measured EICO versus fuel flow for the PW305

Predicting the emissionindex for CO with SLS-data but without a correction (dashed line) would lead to higher values than the measured values for 43000 and 50000ft.

5. SENSITIVITY

In this chapter assessments of senstivity effects concerning the used fuel and the produced emissions for typical aircraft engine combinations are presented.

The Airbus A340-300 with CFM56-5C2 engines and a takeoff weight of 240t is used for the following investigation. The mission-range is 8200 km and the cruise Mach-number is Ma=0.82 at an altitude of 10670 m. Figure 18 shows the calculated percentage change of specific data during cruise using two segments with correction described in chapter 2.

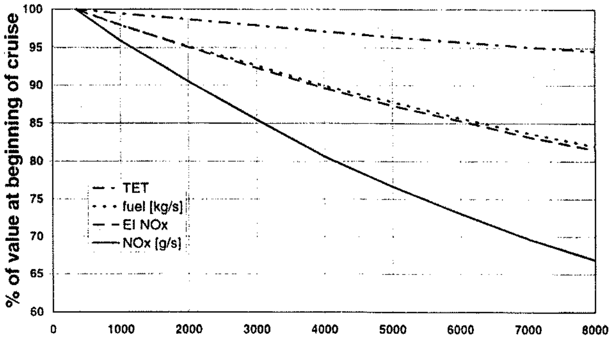

Figure 18: Change of specific data during cruise

To evaluate the influence of the Take-Off weight on the total mission fuel and NO_x including takeoff, climb and descent the Boeing B747 with a CF6-80C2B1F and the Boeing B737 with a CFM56-3B-2 are used as reference aircrafts. The cruise Mach-number of the B747 is 0.86 in 11875 m, the Mach-number of the B737 is 0.77 in 10670 m. The percentage changes of the fuel amount and the NO_x produced per 1% increased takeoff weight are calculated. The calculated data are given in Table 3.

For all calculated missions the percentage fuel change is smaller than the T/O-weight change, the NO_x change is at least as big as the weight change and strongly dependend on the mission range.

The amount of produced CO and UHC remains nearly constant due to an increased fuel consumption and a decreased emission index at the higher power settings of the heavier aircraft.

Another important and very complex influence on a flight mission is the ambient air temperature. Among others it has consequences on the specific fuel consumption, the lift to drag ratio and the ground speed at constant Mach-number. Results of mission calculations with a Boeing B747 powered by RB211-524D4 engines at changing air temperature in comparison to the temperature derived from ISA standard atmosphere can be seen in Table 4. The cruise Mach-number is set constant to 0.86 at 11875 m and the T_{t4}-value is the turbine entry temperature at the middle of cruise at the beginning of the second segment.

Although the necessary TET value to balance the drag of the aircraft changes, the effect on the fuel consumption is relatively small (for example due to the higher SFC at reduced trip time). But the results show a significant influence on the calculated production of NO_x, CO and UHC. For instance, a warm day increases the emission of NO_x but decreases the CO and UHC value drastically due to higher combustor inlet temperature and better combustor efficiencies.

Aircraft:	B747	B747	B737	B737
Mission range (km):	8000	1000	2000	500
Fuel change (%):	0.83	0.61	0.73	0.74
NO_x change (%):	1.50	0.99	1.23	1.03

Table 3: The percentage increase of fuel and NO_x per 1% increased T/O-weight

Δ T (K)	T_{t4} (K)	t (min)	fuel (t)	NO_x (kg)	CO (kg)	UHC (kg)
-5	1255	550	94.5	2157	443	144
0	1287	543	94.9	2354	360	117
+5	1315	537	94.7	2551	294	97

Table 4: Results of mission calculations with a Boeing B747 powered by RB211-524D4 engines at changing air temperature in comparison to the temperature derived from ISA standard atmosphere

6. SUMMARY

In this paper some investigations concerning emission calculation relationships for aircraft engines are presented. Within this publication NO_x-, CO- and UHC-emissions are of main interest. These kinds of combustion products are not only connected with the fuel flow, they also depend on the combustion process itself.

Common emission correlation methods require several engine parameters such as combustor inlet pressure and temperature, air flow and fuel flow. Therefore it is essential having an aircraft and an engine performance program, delivering all required input values.

A short overlook dealing with the aircraft and engine performance program is given. Using these developed tools, good agreement between predicted engine operating parameters and manufacturer's values could be found.

When applying the emission correlation methods to predict the emissions in flight for any aircraft engine, it should be possible to simplify the commonly used relations. These newly developed methods should only take into account the available cockpit data, such as fuel flow and ambient conditions and should be nearby as accurate as the more 'complex' emission correlations. From similarity rules especially for the NO_x emission index a simplification in the calulation procedure could be derived. The validation of the new developed - so called fuel flow method - could be done only qualitatively with test data for the RB211-engine.

A connection between combustor loading parameter and CO- and UHC-emission indices are obtained. Finding an analytical function describing the amount of emitted carbonmonoxid and unburned hydrocarbons versus loading parameter also a more simplified correlation method for these species could be found. Using mesasured emission data for the small turbofan engine PW305 the new derived calulation procedure could be confirmed as well.

A sensitivity analysis concerning ambient temperatures shows a significant influence on NO_x and especially CO and UHC production.

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