OPTIMAL MISSION ANALYSIS ACCOUNTING FOR ENGINE AGING AND EMISSIONS

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- **Mission Analysis Model**
  - **General Description**
  - **Flight Mechanics-Equations**
  - **Sub Models**
  - **Example Application**
- **Optimization of Flight Trajectory**
  - **Problem Definition**
  - **Optimization Method**
  - **Optimization Scenarios**
- **Pollutant Emissions Estimation**
- **Discussion**

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Mission Analysis Model

- ☞**CAMACM: Commercial Aircraft Mission Analysis Computational Model.**

- ☞**Covers all segments of a modern commercial aircraft typical flight:** taxi, take off, climb, cruise, descent and approach

- ☞**It analyses the trajectory (in X-Z plane) of the aircraft, by using the basic Flight Mechanics' longitudinal equations of quasi-equilibrium between the applied forces.**

- ☞**It allows the analysis of a variety of possible missions within the limits of safety and traffic regulations.** (inputs: mission length, payload and fuel, cruise altitude and velocity, climb and descent desired trajectory, <u>Engine degradation level</u>)

- ☞**It delivers the overall mission results:** aircraft trajectory, engines operating points along the mission, burned fuel and flight duration, <u>Pollutant emissions production</u> during flight.

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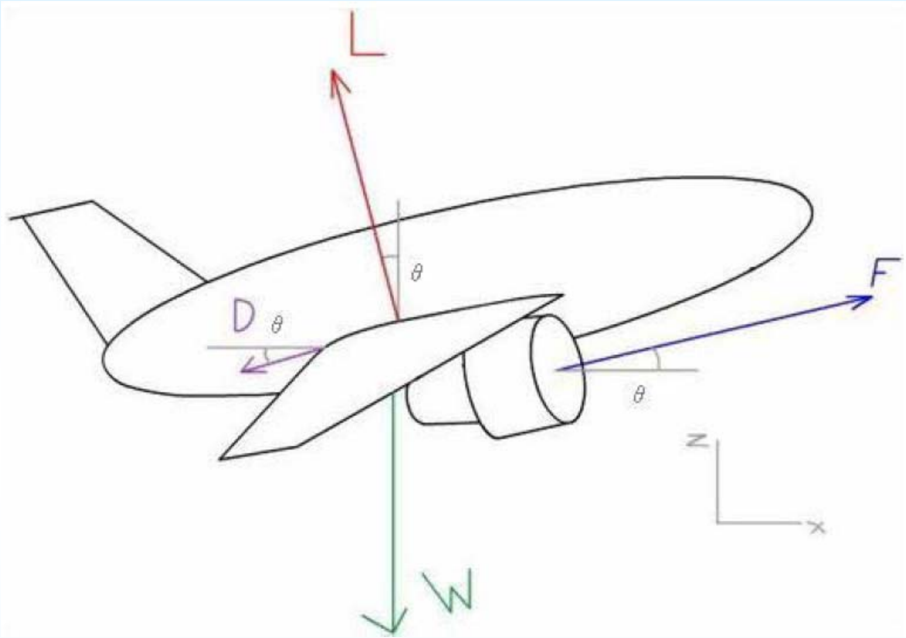
Flight Mechanics-Equations



$$\Sigma\vec{F} = \vec{F}+\vec{W}+\vec{L}+\vec{D} = \frac{d\left(m\cdot\vec{U}\right)}{dt} = \frac{dm}{dt}\vec{U}+m\frac{d\vec{U}}{dt}$$

$$\Downarrow$$

$$\begin{bmatrix}\left|\vec{F}_i\right|\cos\theta\\ \left|\vec{F}_i\right|\sin\theta\end{bmatrix}+\begin{bmatrix}0\\ -m_i\left|\vec{g}_i\right|\end{bmatrix}+\begin{bmatrix}-0.5\rho_i S C_L\left|\vec{U}_i\right|^2\sin\theta\\ 0.5\rho_i S C_L\left|\vec{U}_i\right|^2\cos\theta\end{bmatrix}$$

$$+\begin{bmatrix}-0.5\rho_i S C_D\left|\vec{U}_i\right|^2\cos\theta\\ -0.5\rho_i S C_D\left|\vec{U}_i\right|^2\sin\theta\end{bmatrix} = -\left|\dot{W}_f\right|\cdot\begin{bmatrix}\left|\vec{U}_i\right|\cos\theta\\ \left|\vec{U}_i\right|\sin\theta\end{bmatrix}+\frac{m_i}{\delta t}\cdot\begin{bmatrix}\left|\vec{U}_{i+1}\right|_X-\left|\vec{U}_i\right|\cos\theta\\ \left|\vec{U}_{i+1}\right|_Z-\left|\vec{U}_i\right|\sin\theta\end{bmatrix}$$

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Sub Models (I)

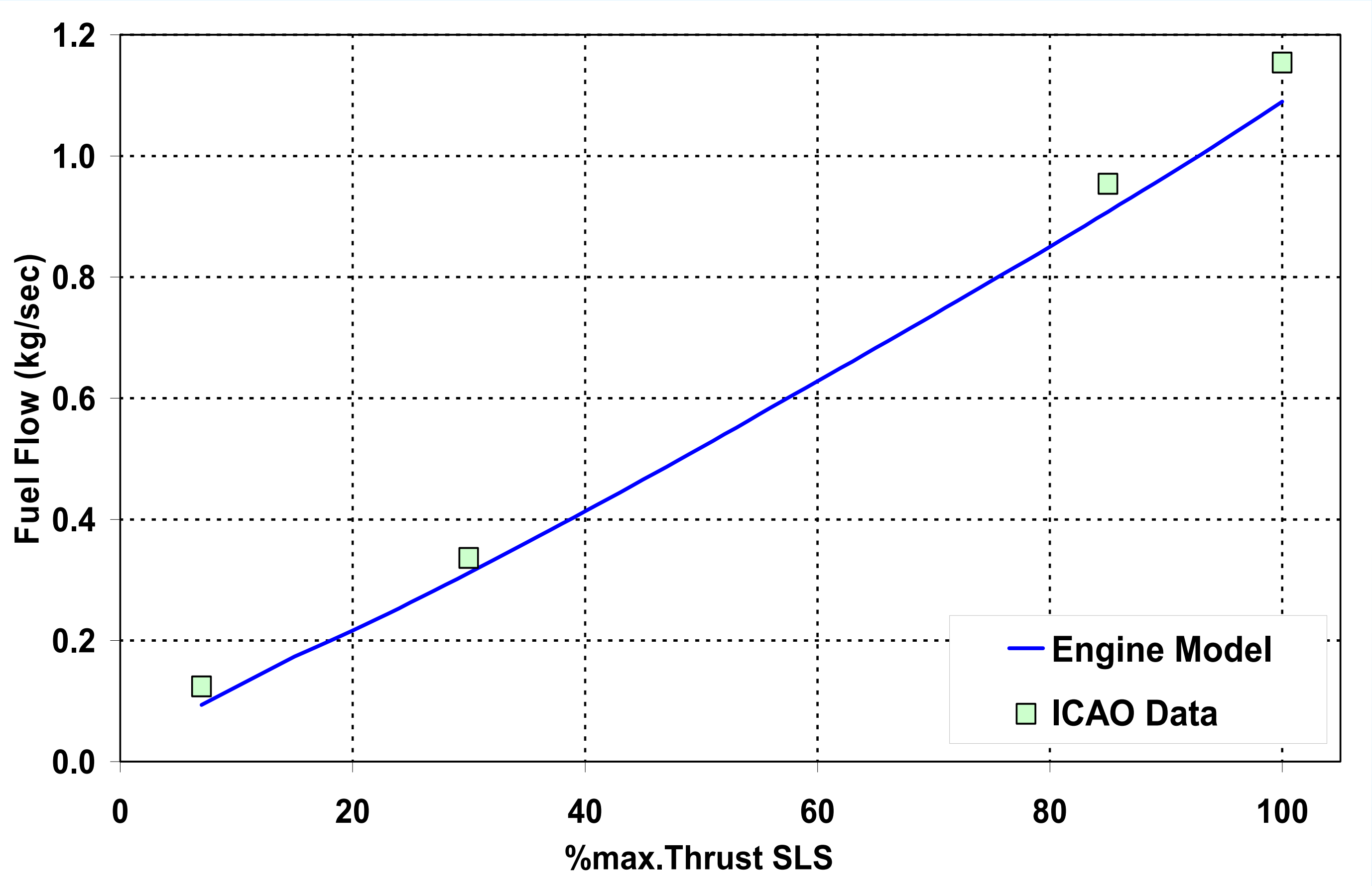
☞**ATMOSPHERE:** provides the ambient conditions during the flight (International Standard Atmosphere-ISA)

☞**AERODYNAMICS:** generic aircraft aerodynamic model, comprises a set of drag polar curves $C_D=F(C_L)$ for a variety of typical High Lift Devices settings. It also takes into account the flight Mach number and the ground effect.

☞**ENGINE:** numerical performance model of a modern high by-pass turbofan engine, (adapted to GE-SNECMA CFM56-3C1 using ICAO databank).

- ➢can handle engine degradation through the use of Engine Condition Parameters (ECP)
- ➢can be used to simulate the effects of engine components degradation (compressors, turbines) on overall performance.

Sub Models (II)



Comparison of predicted (engine model) and ICAO published data

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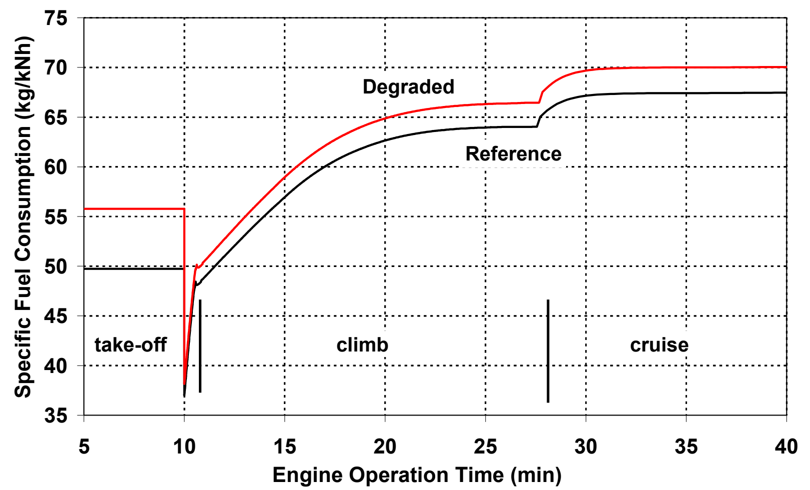
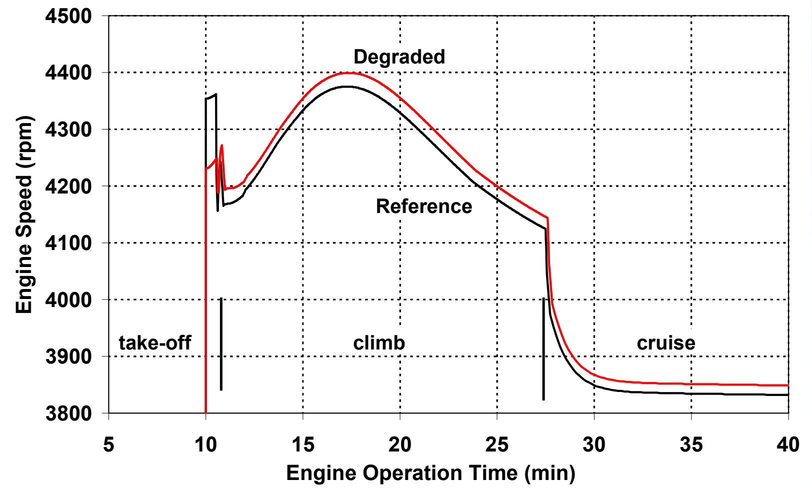
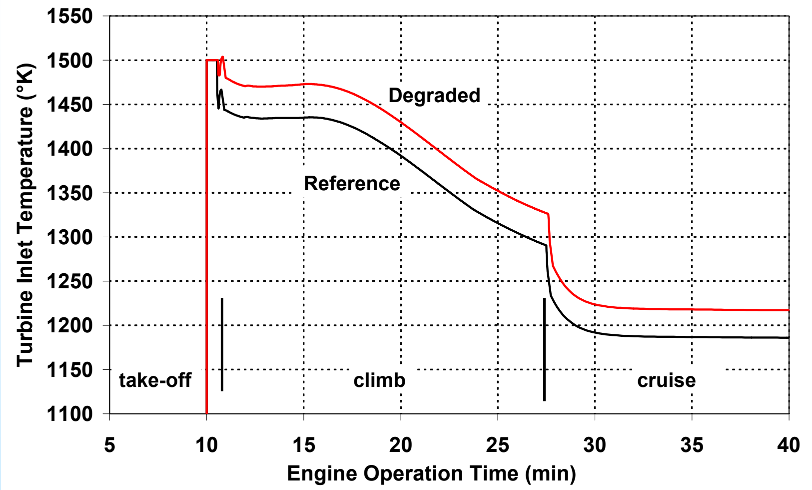
Example Application







A typical mission for different engine conditions

Distance	**2000 km (1080 nm)**
Flight Altitude	**35000 feet (constant)**
Cruise Speed	**M0.8 (constant)**
Payload	**12.6 tons (120 pax + 5 crew)**
Fuel boarded	**7 tons (reserves incl.)**

Indicative Results

Fuel Burned Reference	**4777 kg**
Fuel Burned Degraded	**4942 kg (+3.5%)**

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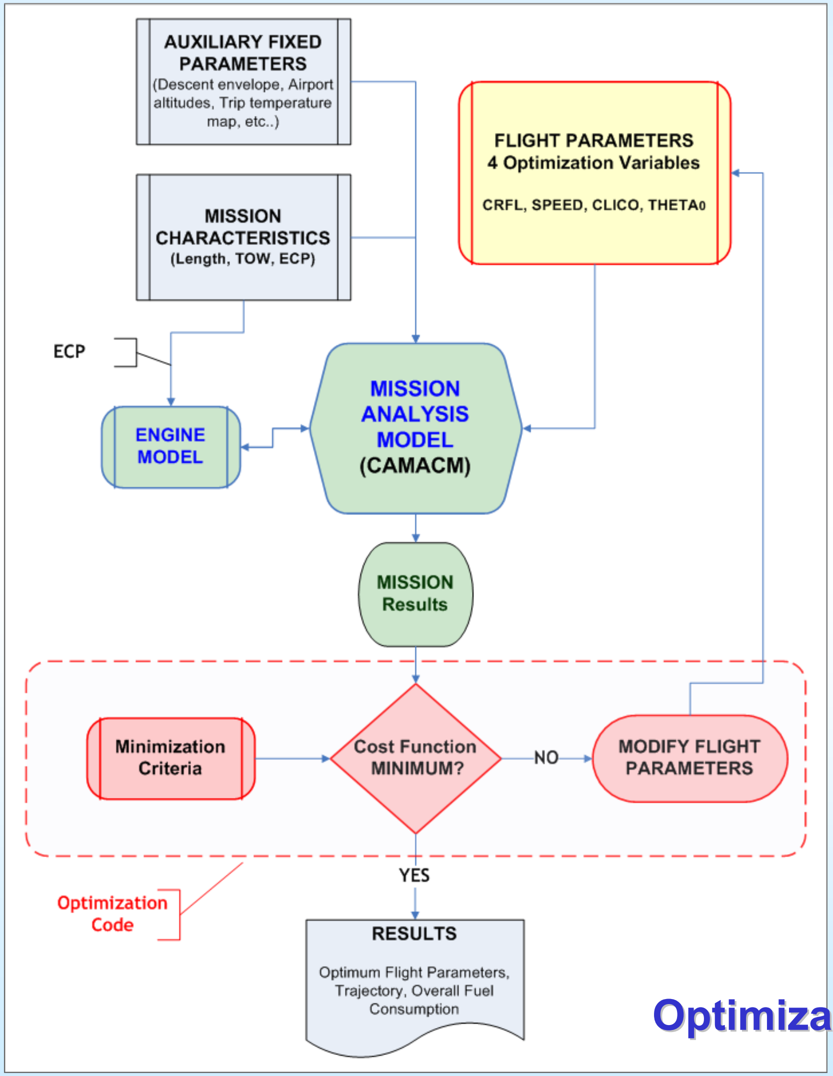
Optimization Of Flight Trajectory



Optimization Procedure

Optimization Variables

Variable	Initial value	Upper constraint	Lower constraint
THETA0 (deg)	8	15	5
CLICO	1.10	1.25	1.00
CRFL (ft.)	36000	37000	26000
CRSP (Mach)	0.8	0.82	0.67

Theta0: Climb gradient
CLICO: Climb coefficient
CRFL: Cruise Flight Level
CRSP: Cruise Speed

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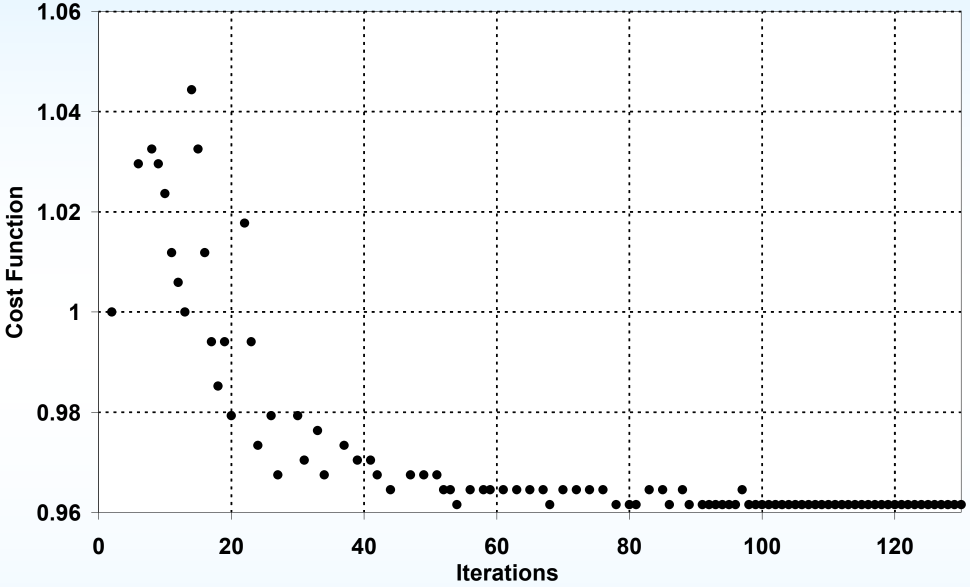
Optimization Method

Minimization of a formulated cost function

$$CF = C_{w_1}\frac{Fuel}{Fuel_{ini}} + C_{w_2}\frac{Time}{Time_{ini}}$$

In the presented applications: only total fuel consumption was considered (No available data for time related costs)

Minimization Method: Simplex Downhill Method in Multi-dimensions



Convergence history for a typical optimization case

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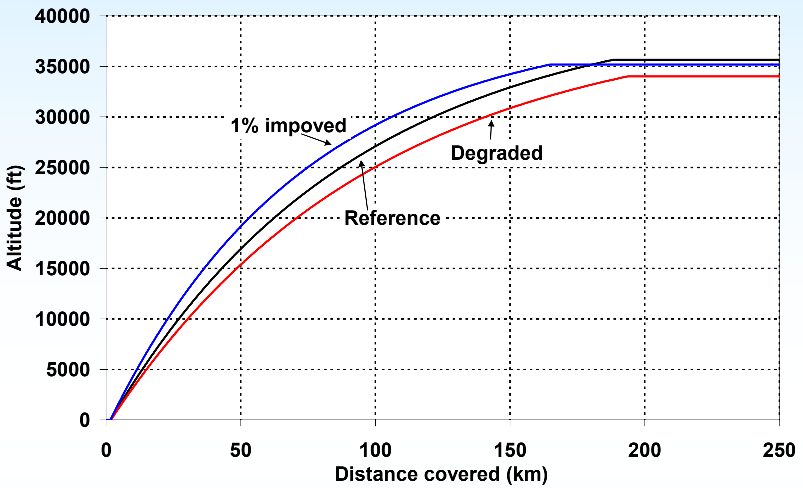
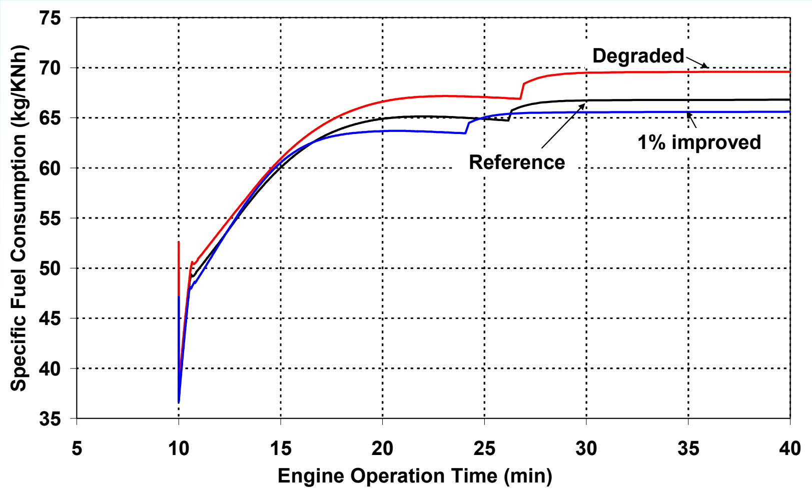
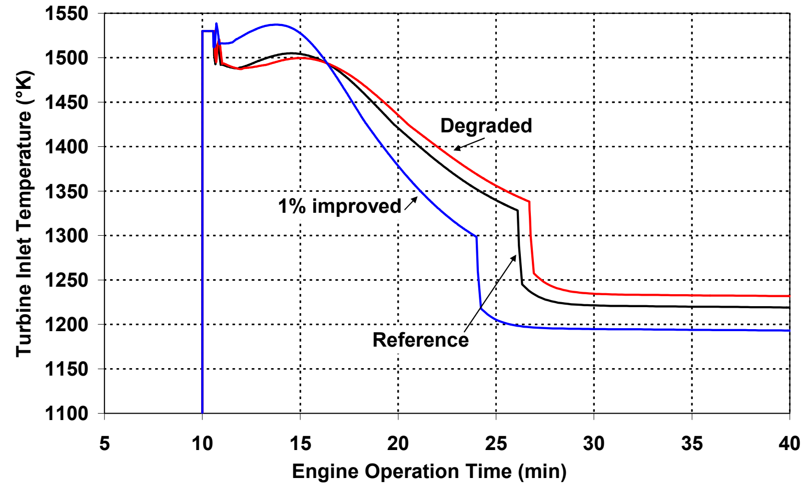
Optimization Scenario 1: Engine Deterioration Level



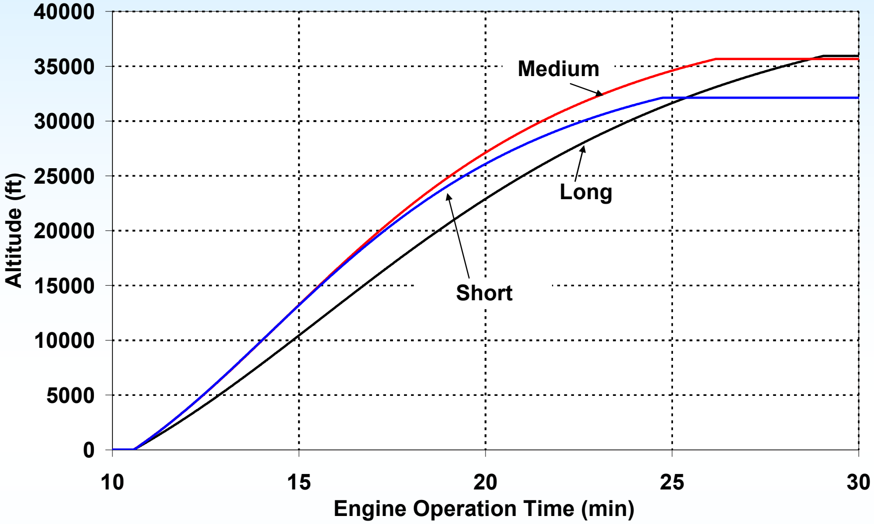




Mission lenght:1500 km, TOW= 58.8 tons, different engine conditions

Engine Conditions	Optimized Values			
	CRFL (ft.)	CRSP (Mach)	THETA0 (deg)	CLICO
Degraded	34000	0.818	7.0	1.244
Reference	35700	0.819	7.9	1.250
Improved	35200	0.820	9.4	1.249

Optimization Scenario 2: Mission Length

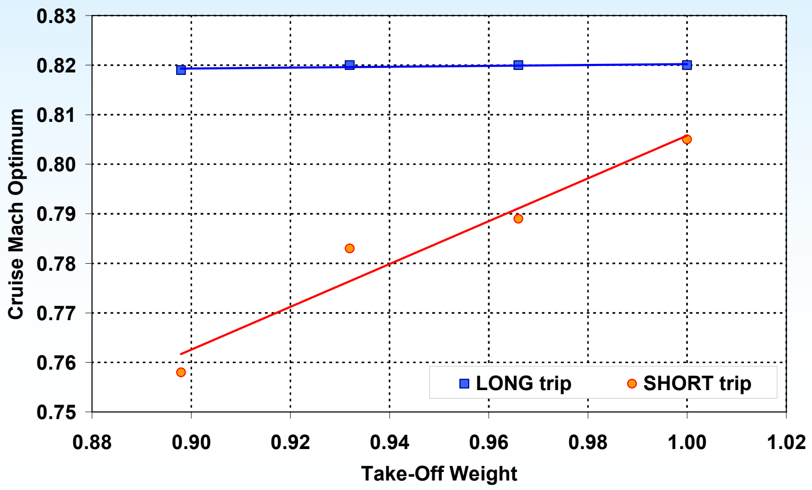


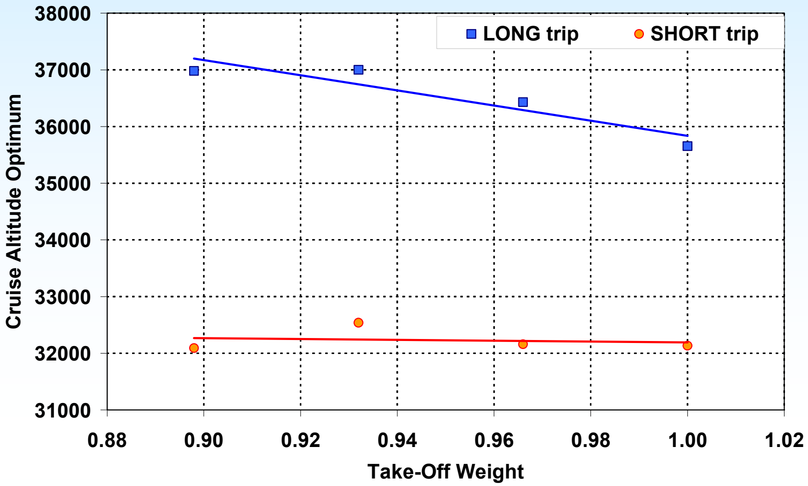
TOW= 58.8 tons, different mission lengths

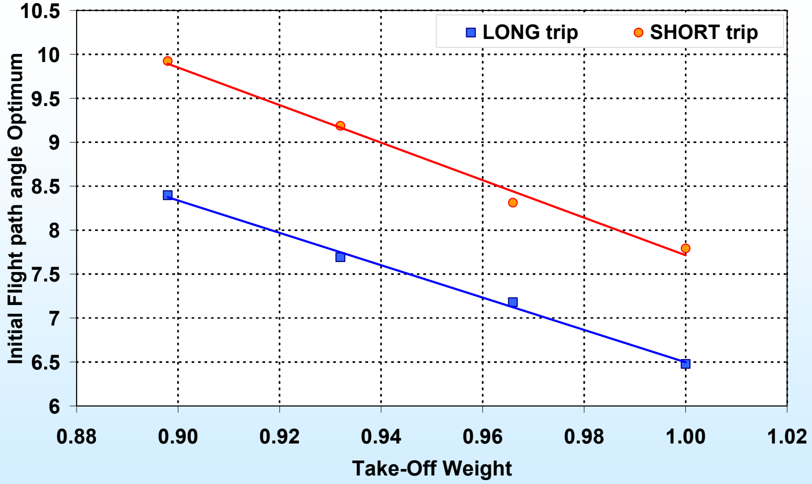
Mission Length	Optimized Values			
	CRFL (ft.)	CRSP (Mach)	THETA0 (deg)	CLICO
A: 500 km	32100	0.805	7.8	1.25
B:1500 km	35700	0.820	7.8	1.25
C:2500 km	35900	0.819	6.5	1.24

- Medium (B) and Long trip (C) differ only in climb phase with a steeper climb for the second one.
- Short trip (A) demands both lower flight altitude and speed
- These results are very close to typical cruise speeds and altitudes for medium-short flights

Optimization Scenario 3: Take-Off Weight







Two mission lengths for different TOWs

- **Long Mission: optimum cruise speed not affected, small dependency for flight altitude**
- **Short mission: cruise speed increases while altitude remains almost constant.**
- **For both missions optimum climb angle reduces with TOW**

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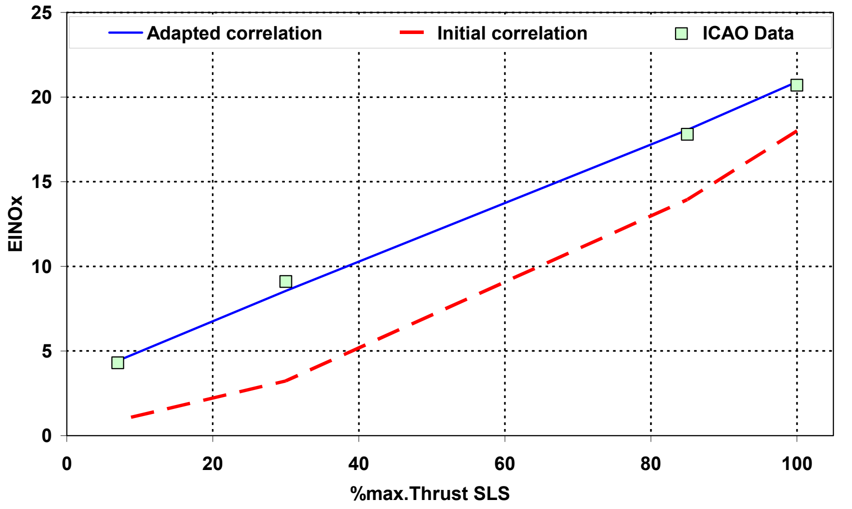
Pollutant Emissions Estimation

A. NOx Correlation

Sullivan’s correlation

$$NOx = C_1 \cdot P_3^{C_2 \cdot 0.5} \cdot e^{\left(\frac{T_3}{C_3 \cdot 300}\right)} \cdot far^{C_4}$$

Is adapted to specific engine using available measurements (in the present case: ICAO databank)



B. CO, UHC Correlations

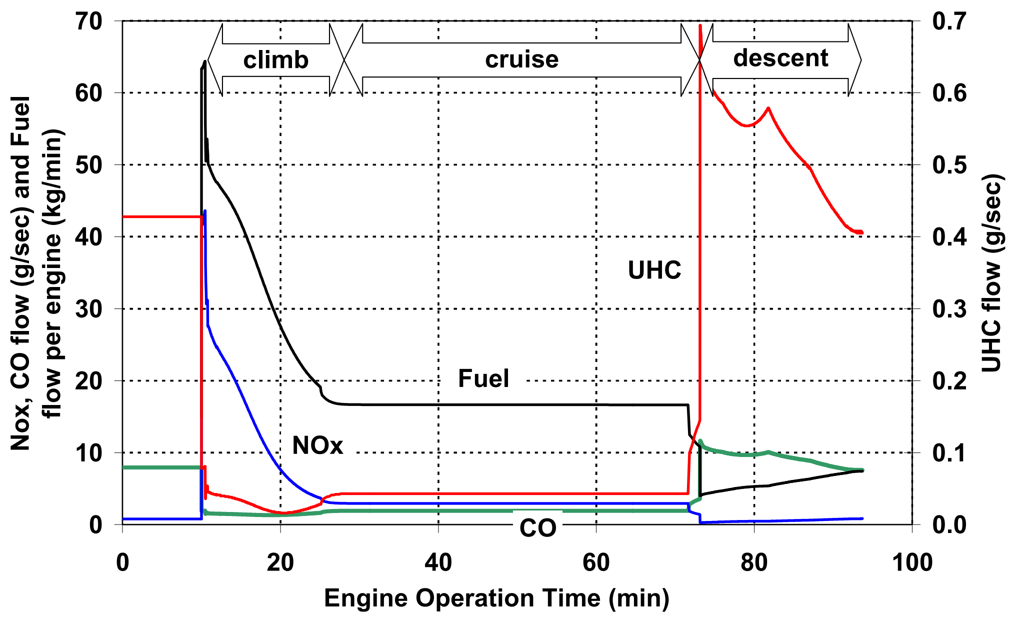
Döpelheuer’s correlations

$$EICO, EIUHC = f\left(\frac{m_{air}}{P_3^{1.8} \cdot e^{(T_3/300)}}\right) \cdot \left\{\frac{T_3}{T_{3,ref}} \cdot \frac{P_{3,ref}}{P_3}\right\}^C$$

These correlations evaluate emissions during flight, based on adaptation to ground level emissions (as for example, those provided at the ICAO databank).

The emissions evaluation module is interconnected to the engine module, to produce emissions data for every point of missions studied.

Emissions Production Rate During Flight



Distance	**1000 km (540 nm)**
Flight Altitude	**30000 feet (constant)**
Cruise Speed	**M0.78 (constant)**
Payload	**120 pax + 5 crew**
Fuel boarded	**7 tons (reserves incl.)**

- **Warm-up / Taxi / Descent:** CO/UHC emissions at very high levels, compared to climb/cruise (4:1 and 10:1).
- **NOx emissions** large for higher power settings (take-off (40-45g/s) / initial climb(20-30g/s)), while very small during cruise (3g/s).
- **This NOx distribution** affects a lot more the departure airport vicinity and the lower atmosphere (first 5 minutes of climb) than the high altitude level (cruise).

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Discussion (I)

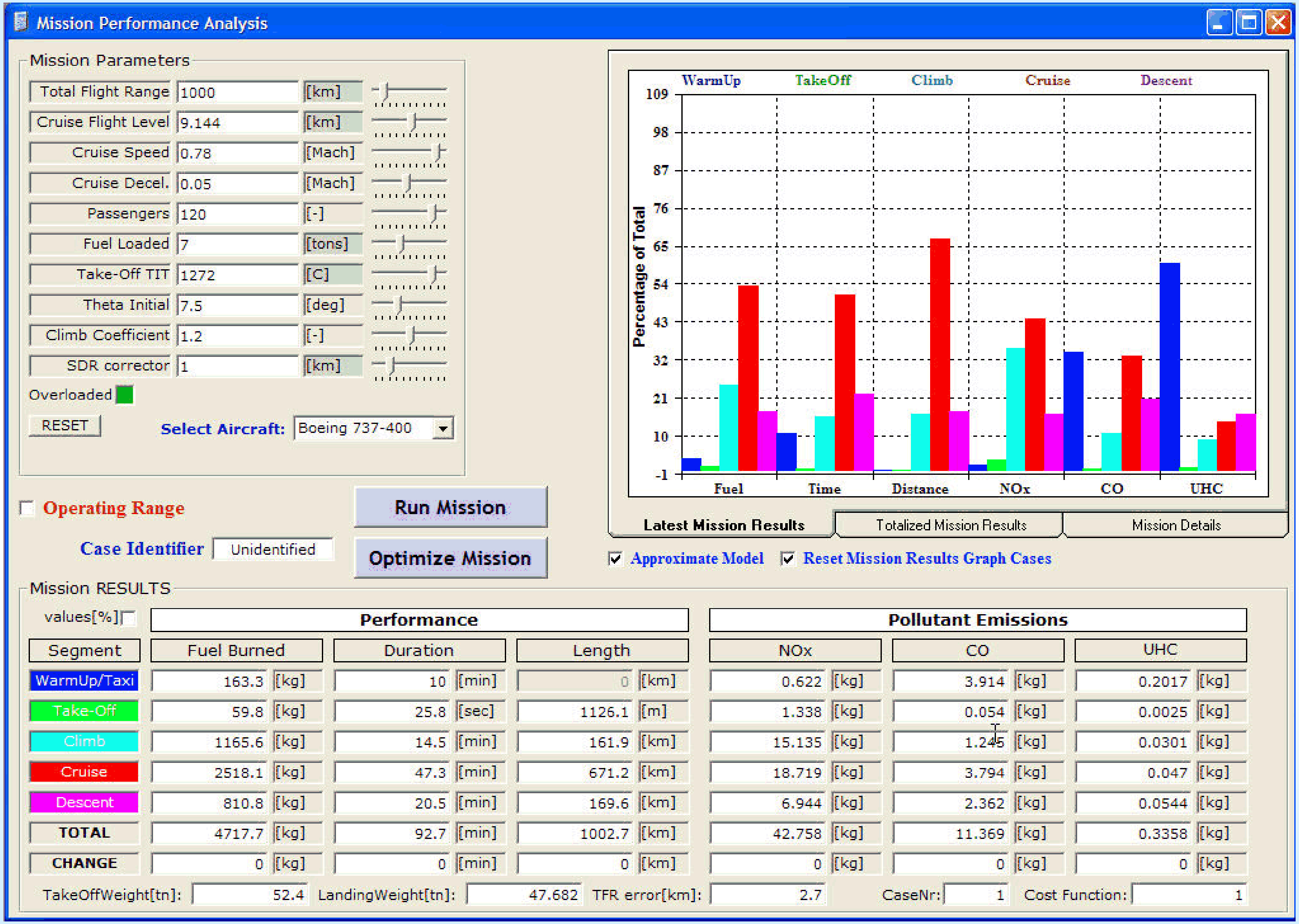
☞**The presented mission analysis model is a useful tool. A variety of investigations can be carried out:**

- ➢**Altering the set of mission parameters, in order to examine the effect on the aircraft and engines performance.**
- ➢**Optimization analysis, for a given aircraft's operation on various missions profiles, or compare different aircrafts best adaptation to the special characteristics of a single mission.**
- ➢**Conducting large scale investigations, concerning fuel conservation and civil aviation's environmental impact, by using the appropriate input data.**
- ➢**Performing a preliminary fleet management investigation, regarding the variation of each individual aircraft's engines condition.**
- ➢**Attaining a better understanding of the modern flight mechanics and aero-engines operation through a realistic comprehensible mission's simulation.**
- ➢**Analyze the "Green Flight" scenario; that is flight trajectory optimization primarily aiming on pollutant emissions and CO_2 reduction.**

Discussion (II)

- The engine model employed is an independent module, externally supplied (flexibility, studies of future engine technologies).
- The proposed mission analysis method requires small time-steps and thus a large number of iterations.
- The computational time can be significantly reduced to a few msecs per mission (very important for optimization), using engine performance data stored into memory (the accuracy penalty is less than 0.5%).
- All modules have been integrated in a single software package with a user friendly interface.

Discussion (III)



Mission Parameters

Total Flight Range	1000	[km]
Cruise Flight Level	9.144	[km]
Cruise Speed	0.78	[Mach]
Cruise Decel.	0.05	[Mach]
Passengers	120	[-]
Fuel Loaded	7	[tons]
Take-Off TIT	1272	[C]
Theta Initial	7.5	[deg]
Climb Coefficient	1.2	[-]
SDR corrector	1	[km]

Overloaded 🟩

Select Aircraft: Boeing 737-400

☐ Operating Range

Case Identifier: Unidentified

☑ Approximate Model ☑ Reset Mission Results Graph Cases

Mission RESULTS

values[%] ☐

	Performance						Pollutant Emissions					
Segment	Fuel Burned		Duration		Length		NOx		CO		UHC	
WarmUp/Taxi	163.3	[kg]	10	[min]	0	[km]	0.622	[kg]	3.914	[kg]	0.2017	[kg]
Take-Off	59.8	[kg]	25.8	[sec]	1126.1	[m]	1.338	[kg]	0.054	[kg]	0.0025	[kg]
Climb	1165.6	[kg]	14.5	[min]	161.9	[km]	15.135	[kg]	1.245	[kg]	0.0301	[kg]
Cruise	2518.1	[kg]	47.3	[min]	671.2	[km]	18.719	[kg]	3.794	[kg]	0.047	[kg]
Descent	810.8	[kg]	20.5	[min]	169.6	[km]	6.944	[kg]	2.362	[kg]	0.0544	[kg]
TOTAL	4717.7	[kg]	92.7	[min]	1002.7	[km]	42.758	[kg]	11.369	[kg]	0.3358	[kg]
CHANGE	0	[kg]	0	[min]	0	[km]	0	[kg]	0	[kg]	0	[kg]

TakeOffWeight[tn]: 52.4 LandingWeight[tn]: 47.682 TFR error[km]: 2.7 CaseNr: 1 Cost Function: 1

http://www.ltt.ntua.gr