# Performance assessment of low-by-pass turbofan engines for low-boom civil supersonic aircraft

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**Abstract.** This paper presents an approach to evaluate the performance of low-bypass turbofan engines without afterburner for a low-boom supersonic aircraft operating at Mach 1.5. The proposed method focuses on optimizing the propulsive performance by minimizing fuel consumption while meeting mission profile requirements. The study contributes to the MORE&LESS project, providing methods for rapidly designing novel supersonic propulsion concepts with improved environmental performance. The research conducts a thermodynamic analysis for on-design engine conditions based on the Modified Specific Heat (MSH) gas model. Specific non-installed thrust and fuel consumption are estimated for cruise phase. Then, the engine cycle analysis is also performed to study off-design performance, including simplified models to account for engine drag and calculate installed thrust and fuel consumption. MATLAB simulations are employed to determine thrust and consumption based on the specific mission profile of the Mach 1.5 case-study, allowing for comparison of different engine types. Ongoing work involves the optimization of engine parameters such as compression ratio, bypass ratio, and turbine inlet temperature, targeting further fuel consumption reduction and pollutant emission estimations.

## Introduction

The next generation of supersonic aircraft is shifting towards low-boom configurations with slender structures and cruising Mach numbers of about 1.5. Extensive research is underway to identify the most suitable propulsion system that can effectively fulfil the specific mission requirements of these aircraft. Low-bypass turbofan engines are currently considered the most promising solution. Therefore, this paper aims at analysing the use of low-by-pass turbofan for low-boom civil supersonic aircraft cruising at Mach 1.5. The proposed approach relies on a series of previous studies. In [1] the performances of the engine were computed performing on-design and off-design analyses. Similar considerations could be done for [2], which focused on the cycle and engine layout of similar boom jet. The aim of this paper is to develop the approach proposed in [4] and [6], in which the engine is designed considering some mission phases estimating fuel consumption and expanding off-design analysis to the entire mission profile.

The initial analysis focuses on the engine's parametric cycle, or on-design cycle, considering the aircraft high-level requirements related to the propulsion system, such as the desired cruise thrust, and geometrical constraints. Subsequently, the sea-level thrust is calculated solving the off-design equations using the Newton-Rapson algorithm. During this phase, limitations to the operation of the afterburner are also considered, in order to minimize the acoustic impact of the engine. Once the engine meets all the requirements and constraints, the main parameters are fixed. The final analysis involves evaluating the Thrust-Specific Fuel Consumption (TSFC) during each phase of ASTOS (Aerospace Trajectory Optimization Software) mission profile. Multiple iterations can be performed to assess the mission average TSFC reduction, which serves as figure of merit for performance comparison. The analyses were conducted using MATLAB routines, which were developed to contribute to the EU-funded MORE&LESS project, providing methods for rapidly designing novel supersonic propulsion concepts with better environmental performance. The high-level requirements of the considered aircraft are in Table 1.

*Table 1. Low-boom supersonic jet high-level requirements*

| Low-boom supersonic jet high-level requirements | |
|---|---|
| Cruise Mach Number | 1.5 |
| Cruise altitude | 16 km |
| Payload | 8-12 passengers |
| Range | 6500 km |
| Propellant | biofuel |

The Methodology section specifies how these requirements were used as inputs to develop an *ad hoc* propulsive system. Outputs in terms of fuel consumption and fuel mass flow rate for different turbofan engine designs are presented in the Results section. Considerations and final remarks are drawn in the Conclusion section.

## Methodology

The workflow adopted is depicted in Fig. 1, while the inputs required to start the analysis are listed in Table 2.

*Table 2. Inputs: Engine requirements*

| | |
|---|---|
| Cruise Thrust | 30 kN |
| SL Thrust | 143.1 kN |
| Inlet Diameter | 1.10 m |
| Number of Engines | 2 |

First, the required thrust during cruise and geometrical constraints (inlet and nacelle size) are considered. On-design analysis is carried out, using altitude and flight Mach number as main inputs. According to [7], two turbofan mixed flows engines are the appropriate propulsion systems configuration for this type of jet. It also possible to consider separated flow turbofans [2], however the increase of fan diameter lead by by-pass must be taken in consideration due to aerodynamics implications. Then, sea-level thrust is computed setting Mach number and altitude equal to zero (sea level static thrust). The mission duration is around 16000 seconds, dived into 486 points, so each step is around 32 seconds. At each step time, a flight Mach number, altitude and required thrust is given, it is possible to calculate the engine thrust from off-design tuning the throttle, to reach required thrust with a residual less 10 N. The inlet temperature is chosen as throttle parameters, varying it until convergence with a step of 2 Kelvin. Additionally, Fig.1 reports the output of engine/mission analysis. It also possible to consider the installation losses due to nacelles.

However simplified model in this paper is adopted for the inlet (Eq. 1) and an average value of 0.03 of uninstalled thrust for the nozzle.

$$T = F - \phi_{inlet} \cdot F - \phi_{nozzle} \cdot F \approx 0.95 \cdot F \tag{1}$$

It is possible to summarize the uninstalled thrust calculations using off-design relationship, reported in the following equation (Eq.2):

$$F \ = F(\ M_0(t_k), Alt(t_k), \tau(t_k)) \tag{2}$$

Known the installed thrust, it is possible to calculate the installed thrust fuel consumption directly, using Eq. 3:

$$TSFC = \frac{\dot{m}_f}{T} \tag{3}$$

Mass fuel rate $\dot{m}_f$ is computed from off-design algorithm using Newton-Raphson method to solve non-linear system of equations. TSFC varies during the mission and the thrust fuel consumption during mission profile is known at each point, so it is possible to optimize the engine achieving the fuel consumed reduction, changing the on-design engine parameters such as by-pass (BPR), overall pressure ratio (OPR) and fan pressure ratio (FPR). For on-design inlet turbine temperature, it is possible to consider the level of technology of the evaluated engine, assign the desired value.

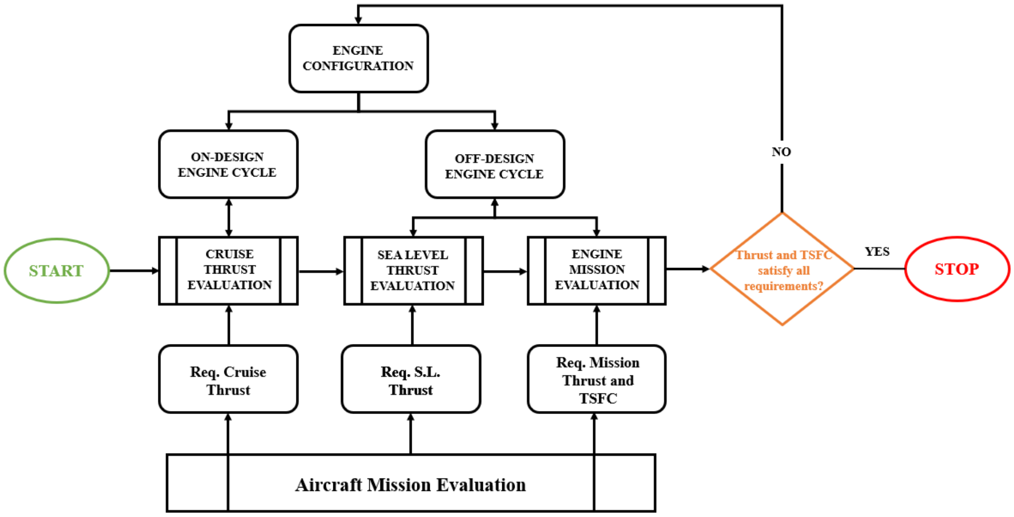

*Figure 1. Methodology workflow*

## Results

The methodology previously described has been used to optimize a turbofan engine for supersonic low-boom jet. Letter B indicates the by-pass ratio and letter O the engine OPR. The compression ratio of the fan is calculated so that the ratio of total pressures inside the mixer is equal to 1 [4]. It is assumed that the power and flow rate spills to the engine to be zero according to a technological level equal to 4 [6] as the efficiencies of the various components that make it up. The starting engine has a bypass ratio of 0.20, and an OPR of 20 (TURB MIX B020-O20). The engine delivers sufficient thrust throughout the mission while consuming about 11121.40 kg of fuel. An attempt can be made to increase the bypass ratio in order to reduce fuel consumption. It is observed that excessive increase in the bypass ratio (0.600) results in insufficient thrust output from the engine. Consequently, the bypass ratio is adjusted to 0.400, and the process is iterated. As can be seen in Table 3, there is a reduction in engine consumption. Another way to reduce the TSFC of the engine is to increase the total compression ratio of the engine, up to a limit value equal to 30.

*Table 3. Engine fuel used.*

| | Single Engine | Two Engine | [%] of fuel saved |
|---|---|---|---|
| TURB MIX B020-O20 | 11121.40 kg | 22242.79 kg | 0% |
| TURB MIX B040-O20 | 8919.91 kg | 17839.81 kg | -20% |
| TURB MIX B040-O24 | 9036.41 kg | 18072.83 kg | -19% |
| TURB MIX B040-O26 | 8625.68 kg | 17251.36 kg | -22% |

Keeping the engine by-pass constant, we can reach up to 26. Note that the TURB configuration MIX B040 O24 has higher fuel consumption than TURB MIX B040 O24. The explanation for these counterintuitive results lies in the numerical error related to the throttle setting during the mission. Fig. 2 and 3 show the fuel flow rate and TSFC values of the four engines.

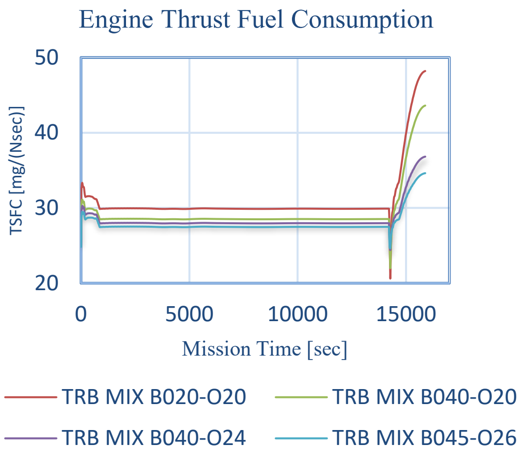

*Figure 2: Engine TSFC*

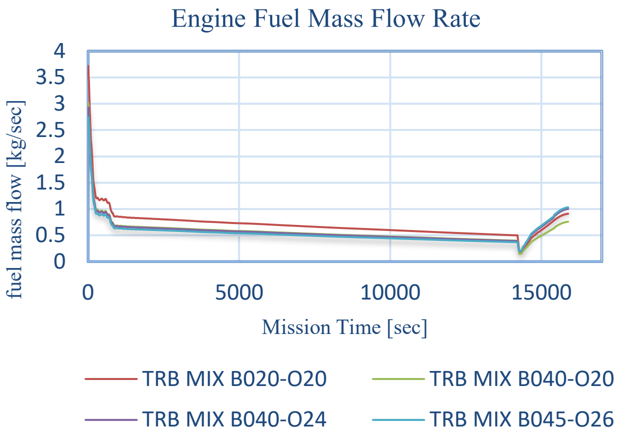

*Figure 3: Fuel Mass Flow Rate*

## Conclusions

The method presented here calculates the performance of a mixed flow turbofan engine for a Mach 1.5 low boom supersonic aircraft, supporting the activities of the MORE&LESS project. Simple equations implemented in MATLAB were used for on-design and off-design thermodynamic cycle calculations. It was found that the model has limitations in throttle adjustment but can still yield results in agreement with literature using minimal input. The method is suitable for preliminary sizing in early project phases, with potential for further improvement in component mapping, throttle adjustment, and emissions modeling.

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