Comparison of life cycle cost for Mach 8 and Mach 5 hypersonic passengers aircraft

COMPARISON OF LIFE CYCLE COST FOR MACH 8 AND MACH 5 HYPERSONIC PASSENGERS AIRCRAFT

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Abstract

Hypersonic aircraft concepts have been studied cyclically over the last decades and are recently emerging again as hot topic of high-speed aviation. The main difference between past and recent studies is that nowadays the interest of private companies and startups in the field of hypersonic aviation for commercial purposes has gain momentum and the sector is no longer a monopoly of military and governmental institutions. However, for commercial institutions, hegemony and technological dominance are less important, while economic profitability and competitiveness is crucial, especially as far as operational concept is concerned. For this reason, a careful cost assessment of the vehicle under study is required already from the initial stages of the design, in order to analyze development, production and subsequent operating/disposal costs. This paper aims at applying existing as well as ad hoc developed cost estimation models for the analysis of these cost categories for two hypersonic long-haul passengers aircraft, characterized by a Mach number in cruise of about 8 and 5 respectively. The idea is to promote a comparison between different architectures and mission concepts in order to understand the impact of vehicle size and operating conditions on final cost breakdown and ticket price for the reference payload.

Keywords: Hypersonic aircraft, High-speed aviation, Hydrogen cost, Life cycle cost, Cost estimation relationships

1. Introduction

Hypersonic aircraft concepts have been studied cyclically over the last decades and are recently emerging again as hot topic of high-speed aviation. The main difference between past and recent studies is that nowadays the interest of private companies and startups in the field of hypersonic aviation for commercial purposes has gain momentum and the sector is no longer a monopoly of military and governmental institutions. Enabling technologies for hypersonic flight, such has high-speed propulsion, airframe-propulsion integration, thermal protection materials, hydrogen storage and management etc…, have raised their readiness level and some companies aiming at exploiting such kind of vehicles for commercial purposes seems to have closed the gap to entry-into-service, with bold announcements stating that civil hypersonic flight may become a reality in the next decade. The technological barrier that was once limiting the practical possibility of operating similar aircraft is surely going to be overcome in the next years, because of the new efforts invested since the 1960s on the topic, but economic viability, sustainability and profitability, especially for commercial concepts, has still to be proven, being the major showstopper for the whole industry. Indeed, development, production and, particularly, operating cost of these vehicles is still a critical aspect to be considered and has to be assessed in order to prevent catastrophic failures of the associated business plan. As for conventional aircraft, design characteristics of the product intrinsically influence the associated value in the different phases of its life cycle, and the subsequent cost, especially during operations, is mainly allocated already at the design stage because of choices made during the very initial sizing phases [1]. Aircraft configuration, mission concept, type of service, payload-

range capability etc… are some of the features that will heavily affect competitiveness of the aircraft during the operating phase, potentially jeopardizing the vehicle cost-effectiveness with reference to competitors (conventional or not). For this reason, a careful cost analysis has to be put in place already at the initial stage of the design, in order to predict the amount of expenses and associated efforts required to support the vehicle during the entire life. As effectively described in [1], operating costs constitute the main contribution within an aircraft Life Cycle Cost (LCC), typically made up of development costs, production costs and operating/disposal costs. Operations-related costs are those faced by the final airline, associated to expenses required to fly the aircraft and manage the fleet, so it is easy to understand why they represent the most important cost category in the whole LCC. However, depending on the perspective, development and production costs may be crucial in the initial phases, for a startup company that aims at developing a new business, for example. In order to assess the whole life cycle of these aircraft in the hypersonic regime, this paper aims at applying existing as well as ad hoc developed cost estimation models for the analysis of development, production and operating costs (disposal costs are neglected) of two concepts for long-haul passengers transportation, derived within EU Funded Projects [2,3], as specified in Section 2, and characterized by a Mach number in cruise of about 8 and 5 respectively. The idea is to promote a comparison between different architectures and mission concepts in order to understand the impact of vehicle size and operating conditions on final cost breakdown, potentially drawing some guidelines and conclusions about the selection of a more profitable vehicle, also starting from relevant studies in literature. A reference ticket price is also estimated.
The paper is organized according to the following structure: Section 2 provides a description of the background of the research, with the analysis of parametric cost estimation methodologies relevant to this work (2.1) and with the introduction of the aircraft case studies (2.2). Section 3 describes the Cost Estimation Relationships (CERs) adopted for the analysis of development, production and operating costs, while Section 4 reports the results for the two vehicle concepts. Ultimately Section 5 draws the main conclusions, summarizing the work performed and briefly discussing the obtained results.

2. Research background

2.1 Cost estimation methodologies from literature

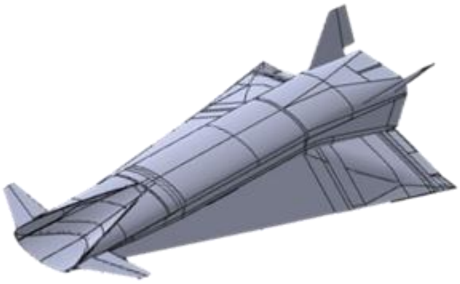
There are different approaches to estimate the cost of an aerospace product. Notably, the three basic cost estimating methods that can be used during the life cycle are the estimation by analogy, the parametric approach and the engineering build-up. The analogy method is based on the analysis of the cost of a similar aerospace system/program, on the application of corrections for differences, and on the subsequent calculation of the cost of the new concept. The parametric approach uses a statistical relationship to relate cost to one or more technical or programmatic attributes (also known as cost drivers). The engineering method (build-up) is a detailed cost estimate built “bottom-up”, estimating the cost of each activity/component in the Work Breakdown Structure (WBS) of a project. In order to directly associate the cost model to the characteristics of the vehicle, also guaranteeing a replicability and repeatability of the analysis, the parametric approach is here selected as method for cost estimation. It has the advantage of being usable already at conceptual design stage, since it is based on mathematical equations (i.e. Cost Estimation Relationships – CERs) that can be derived from high-level parameters or drivers (such as performance, mass, dimensions, etc…), already available at this stage. It does not require detailed program information, as the analogy or engineering build-up approaches, even if a reference statistical database shall be available to build the CERs correlations. This is one of the most critical issue of the cost engineering applied to hypersonic aircraft, since the number of concept/product is limited. However, some models available in literature already tackled the problem, and they can be used, modified, or updated, depending on the specific case study, in the range of applicability, in order to obtain a reliable result starting from a well-established baseline. Particularly, this work uses the cost breakdown suggested by [1] for what concerns the main cost categories, as already mentioned, and notably development costs (also known as Research, Development, Test and Evaluation – RDTE costs), acquisition costs (or production costs plus margin) and operating costs. The model [1] itself however is not directly applicable to this kind of aircraft, being conceived for conventional ones. The TRANSCOST model proposed in [4] is instead closer to the context of this study, since it is specifically developed for space transportation systems, also including algorithms and CERs for the estimation of RDTE and production costs of high-speed winged vehicles, which can be associated to the families of Cruise and Acceleration Vehicles (CAV), Ascent and Re-entry Vehicles (ARV) or winged first stages of Two-Stages To Orbit (TSTO) platforms, as defined in [5]. The model proposes CERs at vehicle and powerplant levels, but it can be used also to develop relationships for on-board systems, where relevant drivers can be expressed, as demonstrated in [6]. This set of relationships is shown in Section 3 and it is here partially revised with reference to [6] in order to improve its effectiveness. Even though the model proposed in [4] also includes a set of relationships for operating costs estimation, it is mainly focused on space systems and it is not suitable for the category of aircraft considered in this study. In fact, as far as operational concept is considered, it is important to retain the typical characteristics of an atmospheric point-to-point mission, which is closer to conventional aircraft operations paradigm, rather than to space-related launch activities. In this case, for example, the operating costs estimation proposed by the already mentioned model from [1] would be more consistent with the mission layout, even though still too much focused on conventional platform. A good compromise is represented by the model proposed by NASA [7], which takes into consideration typical CERs from Association of Air Transport of America (ATA) adding some updates to make them applicable to high-speed aircraft. Also in this case, the complete set of relationships is shown in Section 3 for the different cost items, with focus on the required modifications introduced in this work (especially for what concerns actualization, considering that the model, differently from [4], is older). The models [4] and [6-7] are thus used as basis for this work, in order to perform the estimations provided in Section 4, still maintaining cost categories defined in [1].

2.2 Reference aircraft case studies

Notwithstanding the fact that, recently, some startups and private companies all around the world are investing a considerable amount of efforts in technology development for high-speed flight, also public entities are financing research associated to the topic, with particular focus on environmental compatibility and certification/regulation issues. The European landscape of researches funded on high-speed aviation related topics is a clear example of the interest and positive momentum this sector acquired during the last years, when a series of project such as ATLLAS I/II [8], LAPCAT I/II [9], HIKARI [10], HEXAFLY [11], HEXAFLY Int. [12], STRATOFLY [2] and MORE&LESS [3] have been granted EC fundings from the 6th European Project Framework up to Horizon 2020 schemes. Because of the availability of legacy data, as well as the involvement of authors within some of the aforementioned research activities, this work uses, as case studies, two aircraft concepts identified within the most recent STRATOFLY and MORE&LESS projects.

The first concept is the STRATOFLY MR3 aircraft (Figure 1, left), developed within the "STRATOspheric FLYing opportunities for high-speed propulsion concepts" project. The vehicle is the result of a refinement of the promising LAPCAT MR2.4 configuration, developed within the homonymous project. It is a 94 meters long, 41 meters wide, 400 tons hypersonic waverider capable of carrying 300 passengers over long haul routes (e.g. Europe to Australia, 19000 km) in three hours, flying at more than 30 km of altitude at Mach 8. It features a dual powerplant made of a set of six Air Turbo Rockets (ATR) [13] and a single Dual Mode Ramjet (DMR) [14, 15] powering the aircraft from take-off to Mach 4-4.5 and from Mach 4-4.5 up to Mach 8 respectively. The available thrust at sea level is close to 1700 kN (around 280 kN per ATR engine), while during cruise the DMR can provide 400 kN. The vehicle is powered by liquid hydrogen (LH2) which is used for direct combustion, being stored in distributed cryogenic bubble tanks, reaching a maximum quantity of 180 tons. The waverider configuration ensure an aerodynamic efficiency of about 7 in cruise at Mach 8.

The second concept considered for this study is the MR5 aircraft (Figure 1, right), developed within the "MDO and REgulations for Low boom and Environmentally Sustainable Supersonic aviation" (MORE&LESS) project, which is a follow-up of STRATOFLY, currently ongoing. Considering that the project is focused on supersonic regime, the MR3 case study was re-designed and scaled in order to perform the same mission leg (up to 19000 km) at Mach 5, producing the MR5 concept. It is still a waverider-shaped configuration characterized by an overall length of around 75 meters, the same wingspan of MR3, a take-off mass of about 290 tons and it is capable of carrying more than 200 passengers. It is powered by the same poweplant, even if the scaling process required an update to intake and nozzle areas [3] and the DMR now works on design at Mach 5 conditions. The aircraft is still powered by LH2, with a total capacity of 112 tons. The MR5 was scaled down in order to obtain a smaller vehicle, capable of flying at lower speed and altitudes, to reach more consistent aero-propulsive balance, while carrying less payload, as described in [3]. Available thrust is similar to MR3 at take-off, while in cruise the DMR can now provide 550 kN. Table 1 summarizes the main data of the two aircraft.



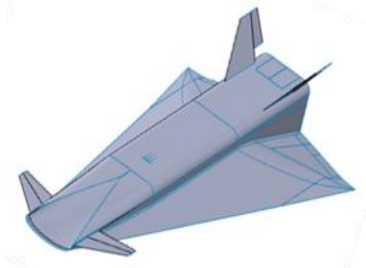


Figure 1 – MR3 (left) and MR5 (right) vehicle concepts used as case studies

Table 1 – Reference data of MR3 and MR5

Data	MR3	MR5
Cruise Mach number	8	5
Maximum Take-off Weight [kg]	400000	288400
Operating Empty Weight [kg]	187000	150000
Vehicle dry weight w/o engines [kg]	161600	124600
Max fuel weight [kg]	180000	112000
Typical range [km]	19000	19000
Payload	300 pax @ 110 kg each	200 pax @ 110 kg each + 4400 kg cargo
Vehicle length [m]	94	75
Wingpsan [m]	41	41
Lift-to-Drag ratio in cruise	6.5	5

3. Life cycle cost model applied for the case studies

3.1 Development costs

Considering the life cycle cost breakdown hypothesized by [1] and assumed in this work as baseline, the first cost category to be assessed belongs to the development costs (also known as Research, Development, Test and Evaluation – RDTE). The TRANSCOST formulation [4] has been used as basis for the development of the updated CERs at airframe and powerplant levels (to obtain vehicle total costs). Additional CERs have been defined as in [6] for the most relevant subsystems, but considering the scope of this work, focused on the comparison of life cycle cost at vehicle stage, they are not discussed in this paper.
The CER associated to airframe-related RDTE costs H_{VA} is reported in (1), as function of vehicle dry mass (excluding powerplant) in kg, and Mach number.

$$H_{VA} = 1746 \cdot \left(M_{dry_{vehicle\,no-engine}}\right)^{0.284} \cdot f_1 \cdot Mach^{0.15} \cdot f_3 \qquad (1)$$

Where f_1 and f_3 are development standard factor (taking into account the novelty of the project with reference to previous activities) and team experience factor respectively, according to [4].

Both MR3 and MR5 use a dual powerplant made up of ATR, which is a Combined Cycle Engine (CCE), and DMR that can be fairly represented as a ramjet. RDTE costs estimation for the powerplant shall then be based on different relationships for the two engines. Even if ATR is a Turbine-Based CCE, integrating a turbojet and rocket architectures, its high-speed nature makes it similar to a ramjet at high Mach numbers in terms of technology, as reported in [6]. For this reason a hybrid formulation has been derived mixing typical turbojet H_{ET} (2) and ramjet H_{ER} (3) RDTE CERs, as described in (4). DMR development costs are instead evaluated using (3) directly.

$$H_{ET} = \left[1380 \cdot \left(M_{ET\,dry}\right)^{0.295} + 1.12 \cdot v\right] \cdot f_1 \cdot f_3 \qquad (2)$$

$$H_{ER} = 355 \cdot \left(M_{ER\,dry}\right)^{0.295} \cdot f_1 \cdot f_3 \qquad (3)$$

$$H_{CCE} = C_{complexity} \cdot (k_{ET} \cdot H_{ET} + k_{ER} \cdot H_{ER}) \cdot f_1 \cdot f_3 \qquad (4)$$

Where $M_{ET\,dry}$ and $M_{ER\,dry}$ represent the dry mass of turbojet and ramjet engines in kg (or mass of related modules, in case of a CCE architecture), and v is the maximum speed at which the engine can be operated in m/s. k_{TJ} and k_{RJ} are coefficients ranging from 0 to 1 so to modify the CER depending on the engine characteristics (if it is more similar to a turbojet, k_{ET} will be closer to 1, otherwise k_{ER} will raise). $C_{complexity}$ is an additional complexity coefficient to take into account development cost escalation in presence of highly innovative technologies involved.

Overall vehicle RDTE cost can be estimated following cost build-up suggested in [4], as reported in (5), where also a relationship to the average Technology Readiness Level (TRL) is introduced, as described again in [6]. In fact, depending on the different progress made in technology development and related researches, it is not always true that the overall RDTE cost has to be sustained starting from scratch. If previous activities allowed to raise TRL, this has to be taken into account. This is in any case a simplified relationship, since TRL cannot be associated directly to a complex object as an advanced aircraft, considering that the index is referring to technologies, rather than to physical equipment. However, a more consistent concept defined as Total Technology Readiness Level (TTRL), bringing together TRL, Manufacturing Readiness Level (MRL) and Integration Readiness Level (IRL) has been studied in [16] as a more robust index to consider other issues associated to object operations, such as maintainability, reliability etc… This is similar to what represented in (5) by the TRL-related parameters, so it is kept and used in a similar way.

$$C_{TOT_{RDTE}} = \left[(1 - K_{TRL}) \cdot f_0^{n_{stages}} \cdot \left(\sum_{i=1}^{N_{ITEMS}} H_i\right) \cdot f_6 \cdot f_7 \cdot f_8\right] \cdot C_{WYr} \cdot \frac{(CPI)_{Target-year}}{(CPI)_{2016}} \qquad (5)$$

Where f_0, f_6, f_7, f_8 are integration, schedule delay, organization and region productivity factors according to [4]. The evaluation shall combine all cost items H_i (airframe and engines), as well as number of stages of the transportation concept n_{stages} if applicable. Moreover, K_{TRL} is the coefficient used to modify the results of the estimation depending on the equivalent TRL (or TTRL) of the technologies involved in the project, ranging from 0 (TRL 1) to 1 (TRL 9). Estimation shall also be consistent with the reference year at which costs analysis is desired, so a Cost Escalation Factor (CEF) shall be introduced, typically as function of Consumer Price Indexes (CPI) ratio between a reference year and the target year.
For the sake of clarity, all estimations are made for 2022 in order to be easy to compare to current costs. Of course, similar vehicles are supposed to start operations in the following decades, so for future predictions, inflation rates of about 2% per year shall be considered at least. Also, TRANSCOST related CERs, such as (1-5) use a unit of measure defined as the Man-Year (MYr) or Work-Year (WYr), identified as the company total annual payroll budget (excluding subcontracts) divided by the number of full-time productive people [4]. This is done to be able to compare different time periods neglecting inflation. In this case, since the estimation is referred to a specific year, results are translated in M€ by applying numerical coefficients suggested by [4] at the end of the formulation C_{WYr}.

3.2 Production costs

Production CERs resemble what already shown for RDTE costs. This means that similar relationships are provided with reference to RDTE CERs, even with different parameters and coefficients. Still, CERs are derived as in (6-9) for airframe F_{VF}, turbojet F_{ET}, ramjet F_{ER} and CCE engines F_{CCE} (using the same build-up in case of CCE), with an overall cost defined in (10).

$$F_{VF} = [0.34 \cdot (M_{OEW})^{1.75} + 7.06 \cdot (v_{cr})^{0.4}] \qquad (6)$$

$$F_{ET} = \left[2.29 \cdot \left(M_{ET\,dry}\right)^{0.53} + 0.5 \cdot v^{0.6}\right] \qquad (7)$$

$$F_{ER} = 5.63 \cdot (T_{ER})^{0.35} \qquad (8)$$

$$F_{CCE} = C_{complexity} \cdot (k_{ET} \cdot F'_{ET} + k_{ER} \cdot F_{ER}) \qquad (9)$$

$$C_{TOT_{PROD}} = \left[f_0'^{n_{stages}} \cdot \left(\sum_{i=1}^{N_{ITEMS}} F_i \cdot f_{4_i}\right) \cdot f_8 \cdot f_9 \cdot f'_{10} \cdot f'_{11}\right] \cdot C_{WYr} \cdot \frac{(CPI)_{Target-year}}{(CPI)_{2016}} \qquad (10)$$

Where f_0',f_9,f_{10}',f_{11}' are production integration, subcontractors, process enhancement and Governmental factors, as defined in [4]. T_{ER} is ramjet thrust in kN, M_{OEW} is the operating empty mass in tons and v_{cr} is vehicle cruise speed in km/h.

The main difference is, however, related to the nature of the cost. Production costs are in fact recurring costs, since they are sustained for each vehicle built. This means that, depending on the number of units, cost is subjected to variation because of the “learning curve” effect f_4. Typically, for the aeronautical domain, this is defined as in (11), and can be interpreted as a 85% cost reduction (P) every time the production run doubles. The factor can be computed depending on the selected production units run, chosen as target n_i.

$$f_{4_i} = (n_i)^{\frac{\log P}{\log 2}} \qquad (11)$$

This is applied to all equations related to production, so to be able of defining a Theoretical First Unit cost (TFU), an average value and a target value at the selected number of unit built (that can be hypothesized as part of the business plan). It is worth noting that ATR learning curve is much more effective than airframe and DMR ones, since for each aircraft 6 ATR need to be built. Ultimately, in order to obtain the acquisition cost, a margin shall be applied to production cost.

3.3 Operating costs

Operating costs are typically divided into Direct Operating Costs (DOC), associated to the flight of a single aircraft and Indirect Operating Costs (IOC), which are associated to fleet management. DOC are more interesting for evaluating the operational costs of the specific aircraft architecture and mission concept, since they can be directly associated to its performance and characteristics, while IOC are more difficult to estimate, since they depend on the specific business model, administration, as well as management effectiveness of the airline operator. Section 3.3.1 reports the CERs for DOC estimation, starting from the baseline defined in [7]. For what concerns IOC, Section 3.3.2 adopts some reference IATA [17] and ICAO [18] values per Available Seat Kilometer (ASK), Revenue Passenger Mile (RPM), aircraft departure or enplaned passenger, as reported in Table *2*.

3.3.1 Direct operating costs

Direct Operating Costs (DOC) typically include fuel, crew, insurance, depreciation and maintenance costs, together with pollution, CO2 and noise charges (airport charges). Considering that airport charges can be different as function of the infrastructure from/to which the aircraft operates and also noting that there is not yet a reference regulation for high-speed aircraft, an average value is considered in IOC for the overall airport and navigation charges.

Fuel DOC CER DOC_{fuel} is reported in (12), while crew DOC_{crew}, insurance $DOC_{Insurance}$, depreciation $DOC_{Depreciation}$ and maintenance CERs are reported in (13-21). Particularly, maintenance is divided into material and labor associated costs for airframe ($DOC_{M/AF/M}$ and $DOC_{M/AF/L}$), ATR ($DOC_{M/CCE/M}$ and $DOC_{M/CCE/L}$) and DMR ($DOC_{M/ER/M}$ and $DOC_{M/ER/L}$) respectively. Costs are computed in $\frac{\$}{ton \cdot statute\ mile}$ in [7], and they can be easily converted in other currencies and units.

$$DOC_{fuel} = \frac{1460 \cdot C_f \cdot \frac{M_{f_T}}{M_{GTO}} \cdot (1-K_R)}{LF \cdot \frac{M_{PL}}{M_{GTO}} \cdot R_T} \qquad (12)$$

Where C_f is the fuel cost in \$/kg, M_{fT} is fuel mass for the mission in kg, M_{GTO} is gross take-off mass of the aircraft in kg, M_{PL} is payload mass in kg, LF is payload load factor, R_T is the range in km and K_R is a factor for fuel reserves.

$$DOC_{crew} = \frac{\frac{320}{M_{GTO}}}{0.725 \cdot LF \cdot \frac{M_{PL}}{M_{GTO}} \cdot Mach \cdot \frac{v_B}{v_{cr}}} \qquad (13)$$

Where v_B is the block velocity (i.e. operational range divided by the elapsed time from engines-on to engines-off).

$$DOC_{Insurance} = \frac{(IR) \cdot \frac{C_{TOT_{PROD}}}{M_{GTO}}}{0.725 \cdot LF \cdot \frac{M_{PL}}{M_{GTO}} \cdot Mach \cdot \left(\frac{v_B}{v_{cr}}\right) \cdot U} \qquad (14)$$

Where U is the utilization in block hours per year.

$$DOC_{Depreciation} = \frac{1.1 \cdot \frac{C_{TOT_{PROD}}}{M_{GTO}} + 0.3 \cdot \left(\frac{F_{CCE}}{M_{GTO}} + \frac{F_{ER}}{M_{GTO}}\right)}{0.725 \cdot LF \cdot \frac{M_{PL}}{M_{GTO}} \cdot Mach \cdot \left(\frac{v_B}{v_{cr}}\right) \cdot U \cdot (L_d)} \qquad (15)$$

Where L_d is the depreciation life of the aircraft in years.

$$DOC_{M/AF/L} = \frac{(3.22+1.93 \cdot t_F) \cdot \left(0.05 \cdot \left(\frac{M_{dry_{vehicle\ no-engine}}}{M_{GTO}} + \frac{M_{AV}}{M_{GTO}}\right) + 0.09\right) \cdot Mach^{\frac{1}{2}} \cdot r_L}{LF \cdot \frac{M_{PL}}{M_{GTO}} \cdot R_T} \qquad (16)$$

Where t_F is flight time in hours, M_{AV} is estimated avionic system mass in kg, r_L is labor rate in \$/manhours.

$$DOC_{M/AF/M} = \frac{(4.52 \cdot t_F + 9.04) \cdot \left(\frac{C_{TOT_{PROD}}}{M_{GTO}} - \frac{F_{CCE}}{M_{GTO}} - \frac{F_{ER}}{M_{GTO}}\right)}{LF \cdot \frac{M_{PL}}{M_{GTO}} \cdot R_T \cdot 10^3} \qquad (17)$$

$$DOC_{M/CCE/L} = \frac{\left(\frac{T}{W}\right)_{GTO} \cdot (1+0.3 \cdot t_F) \cdot \left(\frac{8.6}{\frac{T_{CCE}}{10^3}} + 0.087\right) \cdot Mach^{\frac{1}{2}} \cdot r_L \cdot K_{LCCE}}{LF \cdot \frac{M_{PL}}{M_{GTO}} \cdot R_T} \qquad (18)$$

Where $\left(\frac{T}{W}\right)_{GTO}$ is thrust-to-weight ratio at take-off of the engine, T_{CCE} is engine thrust in N, K_{LCCE} is the labor correction factor (to compare labor complexity with reference to conventional aircraft engines)

$$DOC_{M/CCE/M} = \frac{\frac{C_{CCE}}{M_{GTO}} \cdot (0.011 \cdot t_F + 0.029) \cdot K_{MCCE}}{LF \cdot \frac{M_{PL}}{M_{GTO}} \cdot R_T} \qquad (19)$$

Where K_{MCCE} is the material correction factor (to compare material complexity with reference to conventional aircraft engines spares).

$$DOC_{M/ER/L} = \frac{(1+t_F) \cdot \left(\frac{0.876 \cdot N_{ER} \cdot \frac{L}{D}}{\frac{M_{GTO}}{10^3}} + 0.087 \right) \cdot r_L \cdot K_{LER}}{\frac{L}{D} \cdot LF \cdot \frac{W_{PL}}{W_{GTO}} \cdot R_T} \qquad (20)$$

Where N_{ER} is the number of ramjet modules for the aircraft, $\frac{L}{D}$ is the aerodynamic efficiency, K_{LER} is labor correction factor, as for K_{LCCE}.

$$DOC_{M/ER/M} = \frac{\frac{F_{ER}}{M_{GTO}} \cdot (0.036 \cdot t_F + 0.029) \cdot K_{MER}}{LF \cdot \frac{M_{PL}}{M_{GTO}} \cdot R_T} \qquad (21)$$

Where K_{MER} is material correction factor, as for K_{MCCE}.

3.3.2 Indirect operating costs

Indirect operating costs (IOC) estimation can be difficult since this cost category is subjected to non negligible fluctuations among different operators. Still, they can constitute even 30 or 40% of overall operating costs, so they cannot be forgotten while performing the estimation. Typical cost items of IOC include administration, sales and ground services (passengers, aircraft and traffic management). In this case, as anticipated in Section 3.3.1, charges are also included. Reference values for IOC are reported in Table *2* (costs actualization not yet applied).

Table 2 – IOC Item with reference values from literature

IOC Item	Value	Source	Ref. year
General and Administrative	0.0072 $ per ASK	IATA [17]	2013
Reservation, Sales	0.0076 $ per ASK	IATA [17]	2013
Station and Ground	0.0092 $ per ASK	IATA [17]	2013
Airport, Navigation Charges	0.0083 $ per ASK	IATA [17]	2013
Passengers Service	0.015 $ per RPM	ICAO [18]	2017
Aircraft Service	800 $ per Departure	ICAO [18]	2017
Traffic Service	15 $ per enplaned passenger	ICAO [18]	2017

4. Results

This section provides the results of the life cycle cost analysis for MR3 and MR5 aircraft, together with the assumptions and data used for the estimation.

4.1 Development and production costs for the MR3 and MR5 case studies

Together with the input provided in Table *1*, the following assumptions have been made concerning the main cost drivers and parameters required to populate the CERs for development and production costs, as reported in Table 3.

Table 3 – Cost drivers and parameters to be used as input for development and production costs estimation of MR3 and MR5

Cost driver/parameter	Value for MR3	Value for MR5
Single ATR Mass [kg]	4000	
DMR Mass [kg]	1400	
ATR Maximum operating speed [m/s]	1190	
Cruise speed [m/s]	2427	1495
DMR Thrust in cruise [kN]	400	550
Technology readiness factor K_{TRL}	0.034	
Systems engineering factor f_0	1.04	
Systems engineering factor $f_0{}'$	1.03	
Development factor f_1	1.20	
Team experience factor f_3	0.80	
Productivity of region factor f_8	0.86	
Complexity factor $C_{complexity}$	1.20	
Turbojet configuration coefficient k_{TJ}	0.60 (0.75 for production)	
Ramjet configuration coefficient k_{RJ}	0.40 (0.25 for production)	
Number of produced units n_i	100	
Learning curve factor P	0.85	

Additional coefficients from [4] have been neglected (set to 1).

The results described in Table 4 can be obtained for the analysis of development costs.

Table 4 – Summary of development costs estimation for MR3 and MR5

Cost item	Value for MR3	Value for MR5
Vehicle (w/o engines) [M€]	24740	21414
ATR [M€]	4543	4544
DMR [M€]	1035	1035
Overall RDTE [M€] (including TRL correction and [4] adjustments)	26193	23321

It is interesting to see how the correction factors of [4,6] are influencing the results for the overall vehicle. In fact, a pure sum of the different cost items would lead to almost 31000 M€ for MR3 and 27000 M€ for MR5. Notably, as example, the influence of TRL can be seen in Figure 2, for MR3 (this chart shows only the theoretical correction for TRL, while other factors from [4] are not included).

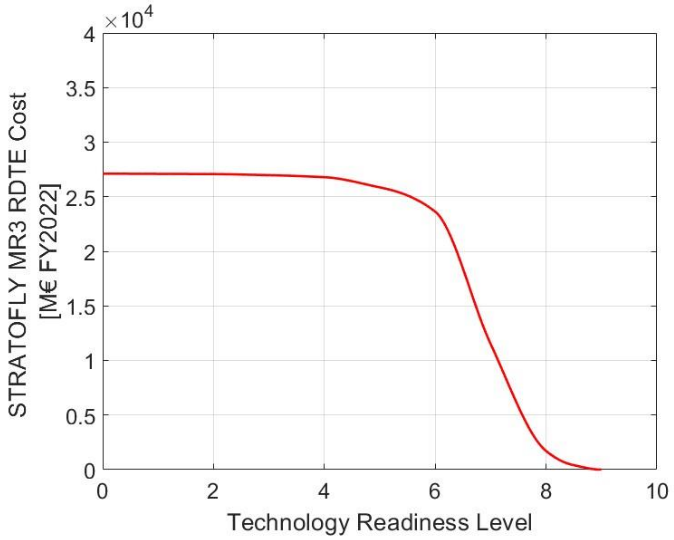


Figure 2 – Effect of TRL correction factor on RDTE cost

These factors are of course subjected to uncertainties (as suggested in [6]), even if the model suggests an associated results fluctuation of about 1-2% only. As it can be seen, for both vehicles, considering the corrected result, more than 90% is devoted to research focused on the airframe, while the remaining amount is devoted to the powerplant (with a more important impact of the low-speed engine). With the hypotheses formulated in the paper, for 100 units, the average development cost allocated on each vehicle can be estimated around 260 M€ for MR3 and 230 M€ for MR5. This translates into 650 €/kg for a single MR3 and around 800 €/kg for a single MR5. Interestingly, the cost per unit mass is higher for the smaller vehicle, since the technology associated to its development does not necessarily scale with vehicle size (on the contrary, a lighter vehicle with the same technology means typically more cost). This can be observed especially looking at the airframe cost per unit mass (powerplant cost is constant per hypothesis).

For what concerns production costs, the cost model is focused on deriving the value for the TFU, that can be then corrected to account for learning curve effect. Table 5 summarizes the results for production costs estimation, looking both at TFU and at average cost for the overall vehicle, considering the production run of 100 units (Figure 3). It is worth noting that the learning curve for the ATR engines is much faster than the one associated to the airframe, since, for each vehicle, 6 ATR are built. The reference cost for the ATR associated to one vehicle is thus an average value of the group made of six engines.

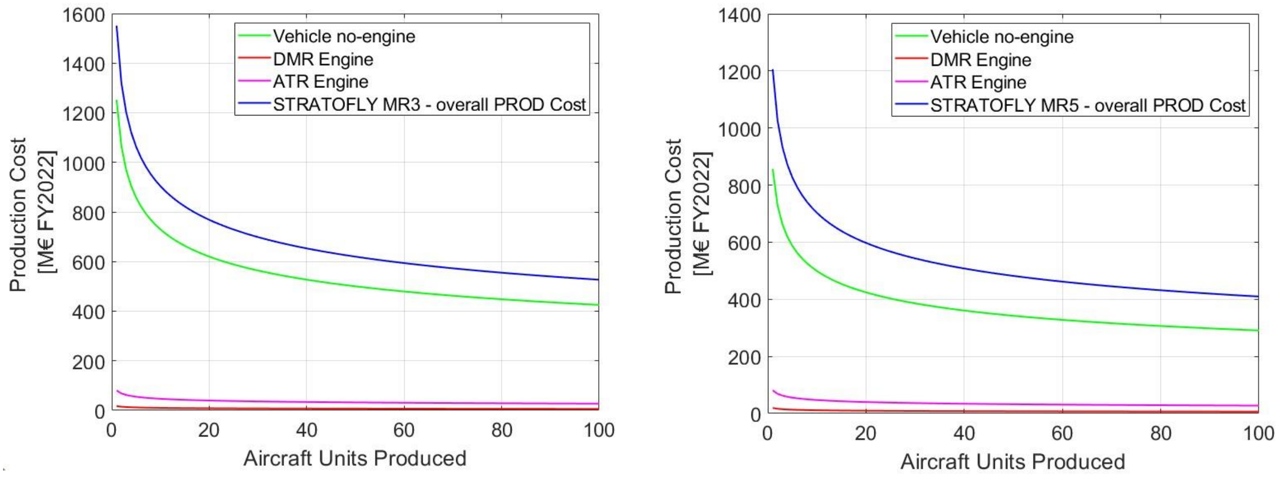


Figure 3 – Learning curve effect on production costs for MR3 and MR5

Table 5 - Summary of production costs estimation for MR3 and MR5

Cost item	Value for MR3	Value for MR5
Vehicle (w/o engines) TFU [M€]	1250	856
ATR TFU [M€]	80	81
DMR TFU [M€]	17	19
Vehicle TFU [M€]	1550	1206
Average vehicle cost [M€]	680	528

The TFU cost is higher than one billion euros for both vehicles, with an average cost for 100 units which is 44% of the first one computed. Also in this case, the absolute cost (per unit) is higher for MR3, but the cost per unit mass, even for production, is higher for MR5 with a value of around 4200 €/kg against 3900 €/kg for MR3. The situation however is more balanced and costs are converging to a similar value with the progression of the learning curve effect. The impact of aircraft size is more evident in this case, also considering that the hypothesis of using the same engine is impacting the results, since the powerplant has a wider impact on the cost breakdown. In fact, almost 40% of the production cost is associated with the powerplant, while the remaining 60% is allocated on the airframe. Small variations of cost associated to engines are due to the slightly different thrust profile for the two vehicles.

4.2 Operating costs for the MR3 and MR5 case studies

As far as operating costs are concerned, the additional considerations specified in Table 6 are applied.

Table 6 - Cost drivers and parameters to be used as input for operating costs estimation of MR3 and MR5

Cost driver/parameter	Value for MR3	Value for MR5
Flight time [hr]	3.40	4.33
Block time [hr]	4.08	5.19
Block speed [m/s]	1294	1015
ATR Thrust per engine (SL – required) [kN]	290	280
Average vehicle price [M€]	990	760
Average ATR price [M€]	80	
Average DMR price [M€]	19	
Fuel price [€/kg]	5.20	
Reserve fuel quantity [%]	8	
Annual insurance rate [%]	2	
Utilization [hr/yr]	2500	
Depreciation life [yr]	10	
Average maintenance labor rate [€/man hr]	35.25	
ATR-DMR Labor correction factor K_{LTJ}, K_{LRJ}	ATR 2.0, DMR 2.0	
ATR-DMR Material correction factor K_{MTJ}, K_{MRJ}	ATR 2.0, DMR 3.0	
ATR-DMR engine time of operation k_{TJ}, k_{RJ} [% flight time]	ATR 35%, DMR 65%	

Notably, a concept of operations based on 2 flights per day - 300 days each year, is considered, with an operational life (i.e. depreciation life) of 10 years. Reference vehicle and engines prices depend on average production cost, development cost allocated on each item and profit margin. Fuel price has been derived following assumptions made in [19,20] on LH2 production scenarios. As result, Table 7 collects the main outcomes of the computation.

Table 7 – DOC breakdown per flight for MR3 and MR5

Cost item [€/flight]	**Value for MR3**	**Value for MR5**
Fuel cost	628600	391100
Crew cost	6900	8700
Insurance cost	23200	18600
Depreciation cost	131400	105700
Maintenance cost	28700	26900
Direct Operating Cost (total)	818800	551000

Table 8 provides different insights concerning DOC associated to hours, distance and carried payload.

Table 8 – DOC for MR3 and MR5 in different units

Cost item	**Value for MR3**	**Value for MR5**
DOC per flight [€/flight]	818800	551000
DOC per block hour [€/bh]	200700	106200
DOC per pax [€/pax]	3640	3060
DOC per pax-km [€/pax km]	0.192	0.161

The cost per unit passenger is referred to a load factor of 75%. The main differences between MR3 and MR5, as shown in Figure 4, are associated to fuel consumption and to capital cost leading to depreciation. In fact, for both vehicles, fuel cost is above 70% of the total DOC, with depreciation between 16% and 20%. If compared to conventional aircraft, the cost per pax-km is 30-50% higher [21], but still competitive considering the technology level of MR3 and MR5, even if maintenance contribution and feasibility of concept of operations shall be further assessed to validate the estimation.

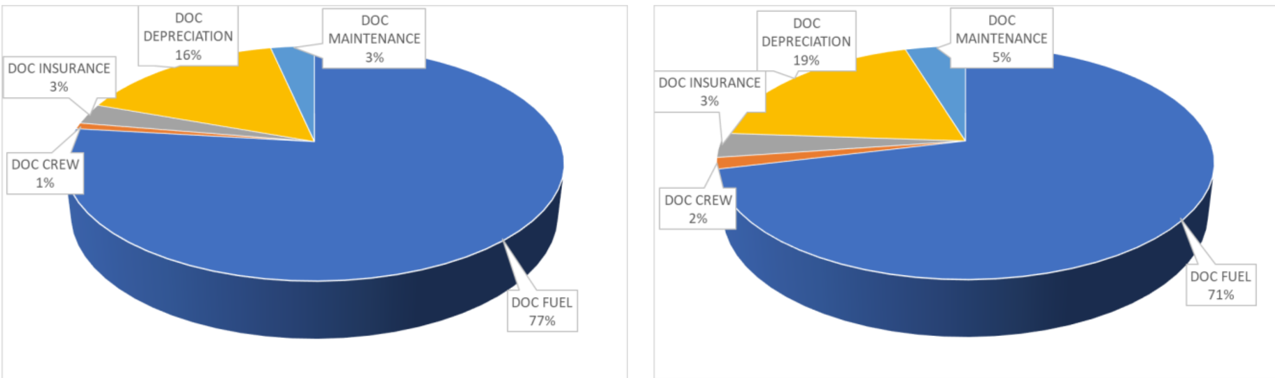


Figure 4 – DOC breakdown for MR3 (left) and MR5 (right)

IOC contribution has been computed according to the values reported in Table 2, as summarized in Table 9.

Table 9 - DOC breakdown per flight for MR3 and MR5

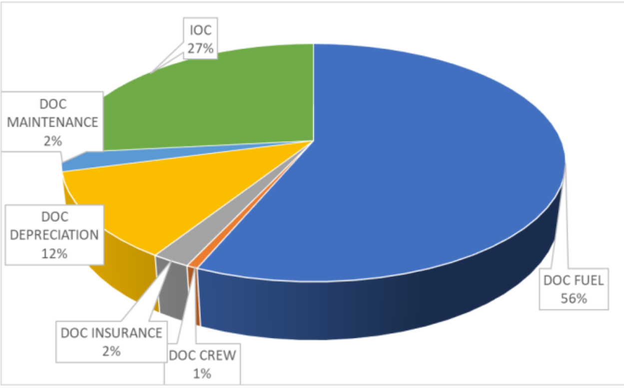
Cost item [€/flight]	Value for MR3	Value for MR5
General and Administrative	49000	39200
Reservation, Sales	51700	41400
Station and Ground	62700	50100
Airport, Navigation Charges	56500	45200
Passengers Service	72800	58300
Aircraft Service	1000	1000
Traffic Service	3800	3000
Indirect Operating Cost (total)	297500	238200

Overall, the TOC breakdown is shown in Table 10 and in

Figure *5*, with a value per flight of around 1.1 M€ for MR3 and 0.80 M€ for MR5. The distribution of the TOC is similar between the two vehicles, even if the higher fuel consumption raises fuel cost contribution, with impact on the total cost, which is above one million euros per flight for MR3. As final outcome, the cost for the passenger is 15% higher when flying at Mach 8, but the ticket price escalation can be limited because of the higher payload (confirming the need of a higher passengers capacity if cruise Mach number increases).

Table 10 - TOC for MR3 and MR5 in different units

Cost item	Value for MR3	Value for MR5
TOC per flight [€/flight]	1116300	789200
TOC per block hour [€/bh]	273600	152000
TOC per pax [€/pax]	5000	4380
TOC per pax-km [€/pax km]	0.261	0.231



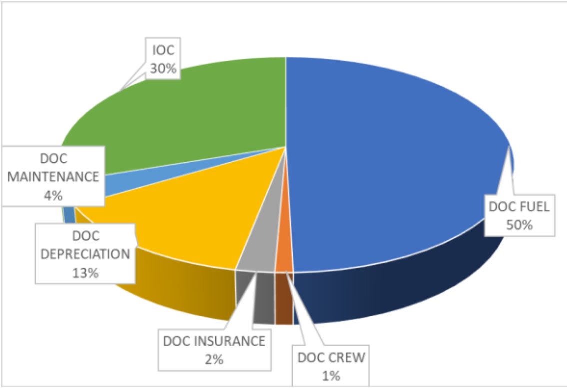


Figure 5 - TOC breakdown for MR3 (left) and MR5 (right)

5. Conclusions

This paper proposed a cost estimation methodology to evaluate the Life Cycle Cost (LCC) of hypersonic vehicles conceived for commercial purposes. The analysis is carried out by both using some existing cost estimation approaches and by introducing modified/new Cost Estimation Relationships (CERs) specifically adapted to support the evaluation of these aircraft families. Notably, two case studies, consisting of hypersonic aircraft conceived to fly at Mach 8 and 5 respectively, have been analyzed from the point of view of development, production and operating costs. Results suggest that, as far as development and production phases are concerned, absolute costs do actually scale with vehicle size and performance, while cost per unit mass is not following a clear scaling rule, considering that tasks such as technology development and production of associated innovative systems may require similar efforts independently of vehicle size. This is particularly evident for the development phase, whilst production is a more variable process, being characterized by a recurrent cost structure. Development costs are in the range of 20 – 30 billion euros, while the Theoretical First Unit (TFU), depending on aircraft size and speed, is estimated around 1.2 and 1.5 billion euros, with estimation performed in 2022. On the other hand, the analysis of operating costs revealed that fuel cost is deeply affecting the costs breakdown, representing 70% of Total Operating Cost (TOC), being associated to the performance of the aircraft in terms of consumption. Capital costs that directly associated to acquisition cost (such as depreciation) are also an important aspect to consider when comparing different aircraft sizes. In the specific example, the smaller and slower aircraft, named MR5 (288 tons, Mach 5, 240 pax) is expected to have a TOC which is 15% lower than the faster and bigger one, named MR3 (400 tons, Mach 8, 300 pax), still keeping the same configuration and poweplant, properly scaled. As order of magnitude, the operating cost per flight is around 1 million euros for this class of aircraft. On the long range, the hypersonic case studies appear to have a cost per pax-km which is 30-50% higher if compared to conventional platform. Also, when increasing speed and size of the aircraft, the adoption of a higher design payload ensures a better economic sustainability in operation. Still, uncertainties concerning the cost model remain and shall be carefully assessed to analyze the margins of the estimation, as well as to assess the flexibility in presence of different aircraft and powerplant configurations. Refinement of CERs is expected, as future works, considering the dynamic evolution of high-speed aviation sector and of clean aviation initiatives, which will deeply affect the availability and cost of green fuels, such as hydrogen, potentially introducing important reduction of economic resources in operations. A continuous validation of the model with reference to the latest case studies developed is thus planned to keep the method up-to-date.

Acknowledgment

This work has been carried out within the frame of “STRATOspheric FLYing Opportunities for High-speed propulsion concepts” (STRATOFLY) project and of “MDO and REgulations for Low boom and Environmentally Sustainable Supersonic aviation” (MORE&LESS) project. This project has received funding from the European Union’s Horizon 2020 research and innovation program under grant agreements No 769246 and No 101006856.

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