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LIFE CYCLE COST ESTIMATION FOR FUTURE REUSABLE ACCESS TO SPACE SYSTEMS

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ABSTRACT

The paper introduces an innovative Life-Cycle Cost Estimation Methodology for future reusable access to space systems to assess Research, Development, Test and Evaluation (RDTE), Production and Operating Costs. In particular, the key limitations of TransCost (i.e., the most comprehensive and noteworthy cost methodology currently applicable to Reusable Launch Vehicles (RLVs)) are discussed, highlighting the need to improve Costs Estimation Relationships (CERs) granularity level to allow a proper down-selection of the most cost-effective design options at early design stage. Therefore, the paper suggests a detailed costs breakdown structure, developed widening the more general subdivision proposed in TransCost, discussing the derivation of new CERs at the desired granularity level. Eventually, after selecting a proper case study, the new cost methodology is applied to verify the effective potential or future RLVs to reduce launch costs.

Keywords: Life Cycle Cost, Reusable Access to Space, Cost Estimation Relationship, Two-Stage to Orbit

1 INTRODUCTION

In the last decades, the integration of costs analysis into conceptual design activities has proven to be a central tool to address the multifaceted features of innovative systems: this capability seems now essential to assess the viability of future reusable launchers. In particular, in a current worldwide scenario characterized by enormous launch costs, reusable access to space systems could represent the only economically sustainable option to manage the continuously growing launch demand. Since the Sixties, several reusable concepts have been studied, culminating into the development of the most complex and technological advanced partially reusable launcher ever built, the Space Shuttle. As it is well known, the great technological complexity of the Space Shuttle highly impacted onto its reliability and, as a consequence, lead to an unexpected increase of launch cost. Nowadays, thanks to the continuous technological progress and new commercial perspectives, a substantial launch costs decrease has been attained for partially reusable systems such as the Falcon 9 from SpaceX. However, the path towards a fully reusable access to space vehicle is still hampered by technological and economic feasibility issues. In this context, the integration of a thorough life cycle cost assessment at conceptual design stage could play a fundamental role in guiding engineers towards the selection of the economical sustainable concepts, avoiding the huge resource wasting experienced in the past.

2 APPLICABLITY OF AVAILABLE COST METHODOLOGIES

As it is well established, cost estimation methodologies are mainly built basing on the heritage from past projects, collecting available cost data and, thanks to dedicated regression techniques, developing ad-hoc Cost Estimation Relationships (CERs). The latter are parametric equations able to assess Research, Development, Test and Evaluation (RDTE), Production, and Operating costs of a product, i.e., its Life Cycle Cost (LCC). As far as future reusable access to space vehicles are concerned, taking into account that, up to now, only the partially reusable Space Shuttle and the Falcon launcher have been effectively realized, the cost estimation process has to face a substantial lack of actual cost data to be used as starting point for the derivation of new CERs. As a result, only few cost estimation methodologies are already available in literature to determine the economic viability of these concepts.

In this context, the most noteworthy and comprehensive cost methodology is the TransCost approach [1] proposed by D.E. Koelle and allowing to assess the overall LCC of a Reusable Launch vehicle (RLV). The method has already been used in the past by the authors to propose an innovative methodology [2] [3] [4] [5] to evaluate costs for future hypersonic cruisers such as the LAPCAT vehicles studied by the European Space Agency (ESA) [6] [7]. Concerning RLVs, TransCost is mostly based on actual launchers cost data but, to provide a preliminary assessment for future reusable launchers, it proposes CERs based on independent cost estimations from classified tools developed in the framework of several studies (e.g., FESTIP [8]). It means that CERs derivation may be based not only on real cost data but, lacking historical costs, they may be built based on cost estimation data coming from previous studies. A thorough analysis of available TransCost CERs clearly revealed that the granularity level of proposed equations was not sufficient to assess the impact of peculiar RLV configurations onto costs. For example, TransCost suggests a CER to evaluate RDTE costs as a function of Vehicle Dry Mass for Winged Orbital Rocket Vehicles, including in this category Vertical Take-Off (VT) Horizontal Landing (HL) Single Stage to Orbit (SSTO) vehicles, HT (with Launch Assist System) HL SSTO and Winged Second Stages of Two-Stage to Orbit (TSTO) such as Shuttle Orbiter or Hermes. As a result, the same value for RDTE cost may be estimated, despite a difference in terms of vehicle type (i.e., SSTO vs. two stages for TSTO). Similarly, the same RDTE CER is suggested for Advanced Aircraft (such as Concorde), Airbreathing SSTO and Airbreathing First Stage of TSTO and rocket engine powered vehicles, forestalling appreciating the impact of airbreathing vehicle types onto costs.

Starting from these considerations, firstly the authors have carried out an in-depth literature review, in order to widen the TransCost database relatively to RLVs. Finally, the updated database has been exploited for the derivation of new CERs at the desired granularity level.

3 PROPOSED COST METHODOLOGY

Figure 1 summarises the LCC breakdown as proposed in TransCost, where RDTE and Production Costs are subdivided considering vehicle airframe (i.e., vehicle structure and on-board systems) and engines separately.

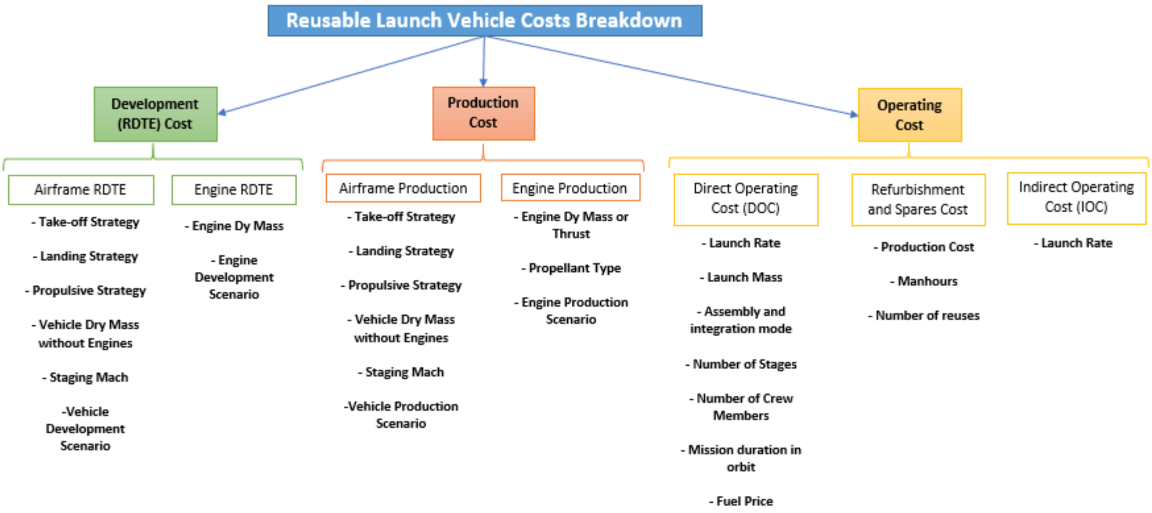
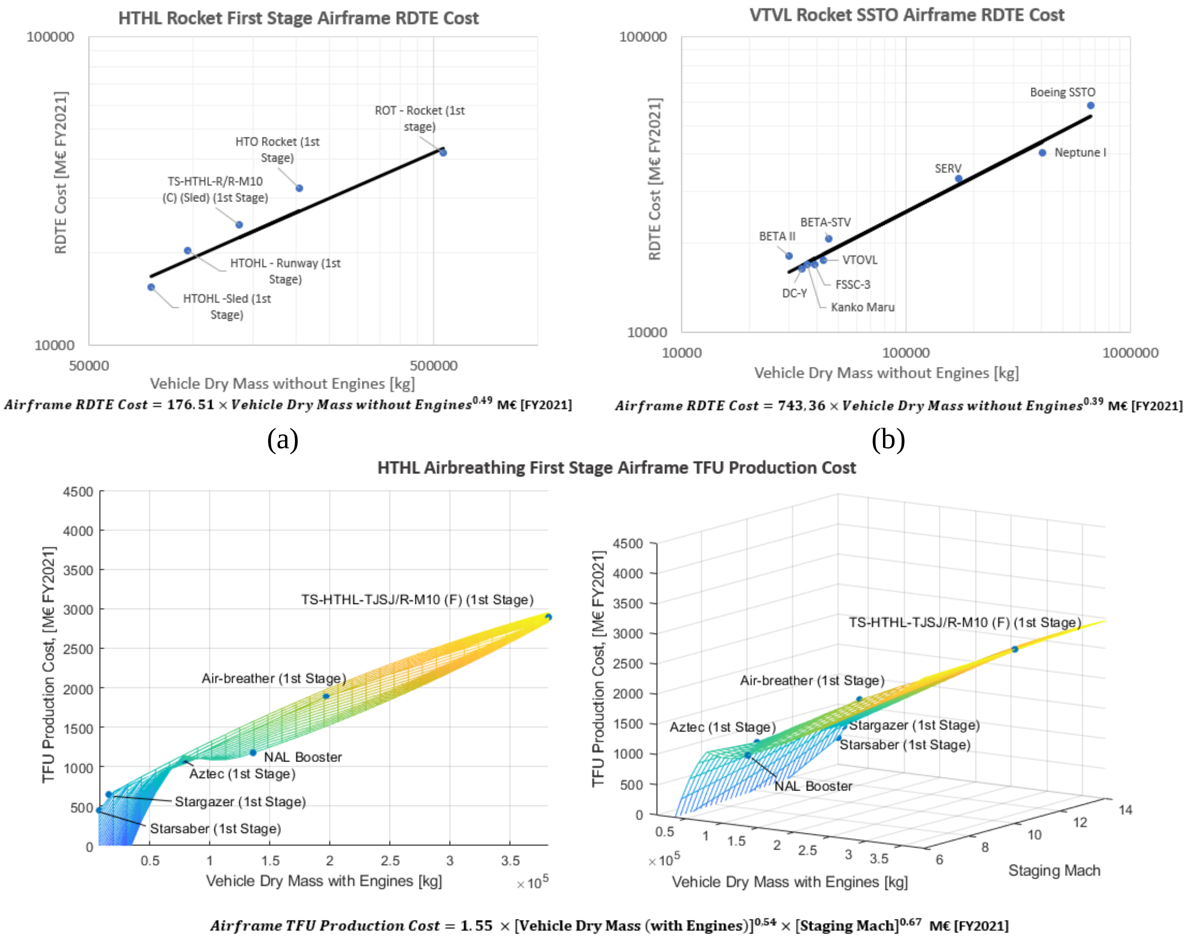


Figure 1: LCC Breakdown for RLVs, cost items and main drivers

As far as Airframe RDTE and Production cost is concerned, new CERs have been derived exploiting the extended database, trying to discriminate on the basis of peculiar vehicle characteristics such as Take-Off Strategy (Horizontal or Vertical), Landing Strategy (Horizontal, Vertical) and Propulsive Strategy (Rocket or Airbreathing) with the aim of assessing the impact of specific high-level design choices onto costs as shown in Figure 2. It is worth noticing that Airframe costs are function of the type of engines installed (i.e. Propulsive Strategy). Concerning engines' cost contribution costs, TransCost CERs for engines' RDTE and Production have been mainly adopted, being able to model key engines' options (i.e., liquid/solid propellant rocket engines, turbojet and ramjet engines). For sake of clarity, Figure 1 highlights the main cost drivers used for the different cost items. For example, following the guidelines provided in TransCost, the impact of Airframe and Engines Development Scenario (e.g., team experience and novelty of the concept with respect to state-of-the-art technologies) has been included using proper correction factors. In addition, exploiting the extended database collected, a thorough evaluation of Staging Mach as cost driver in addition to the classical Vehicle Dry Mass has been carried out. It is underlined that Staging Mach is applicable to TSTO vehicles and represents the maximum Mach number attained by the First Stage before separation from the Second Stage. As an example, the resulting CER for Airframe Theoretical First Unit (TFU) Production cost assessment as a function of both cost drivers is reported and graphically depicted in Figure 2 (c) (resulting costs are expressed in M€ and for Fiscal Year (FY) 2021).



$\mathbf{\mathit{Airframe\ RDTE\ Cost}} = 176.51 \times \mathbf{\mathit{Vehicle\ Dry\ Mass\ without\ Engines}}^{0.49}$ **M€ [FY2021]**

$\mathbf{\mathit{Airframe\ RDTE\ Cost}} = 743.36 \times \mathbf{\mathit{Vehicle\ Dry\ Mass\ without\ Engines}}^{0.39}$ **M€ [FY2021]**

(a) (b)

$\mathbf{\mathit{Airframe\ TFU\ Production\ Cost}} = 1.55 \times [\mathbf{Vehicle\ Dry\ Mass\ (with\ Engines)}]^{0.54} \times [\mathbf{Staging\ Mach}]^{0.67}$ **M€ [FY2021]**

(c)

Figure 2: New CER for Airframe (a) RDTE Cost of HTHL Rocket First Stage; (b) RDTE Cost of VTVL Rocket SSTO; (c) TFU Production Cost of HTHL Airbreathing First Stage

As far as Operating Costs are concerned, as depicted in Figure 1, they encompass Direct Operating Cost (DOC), Refurbishment Cost, and Indirect Operating Cost (IOC). All these costs have been modelled exploiting as much as possible information provided in TransCost. For Refurbishment Cost, lacking specific information in TransCost related to refurbishment (or maintenance) cost of airbreathing engines, the NASA equations for Turbojet and Ramjet maintenance cost already applied for airbreathing hypersonic cruisers in [4] have been used. Is it specified that, as shown in Figure 1, following the

TransCost Refurbishment Cost model, Airframe Refurbishment Cost is a fraction of Airframe TFU production cost.

4 CASE STUDY

The RLV cost methodology briefly introduced in the previous Section has been applied to a selected case study to provide a preliminary overview of the magnitude of LCC expected for future RLVs. In particular, a TSTO vehicle with Airbreathing First Stage (or Booster) and Rocket Second Stage (or Orbiter) described in [9] has been considered. Main characteristics of the vehicle under analysis (herein referred as TSTO-AB) are shown in Figure 3. Table 1 collects RDTE and Production cost results obtained from the developed methodology. Figure 4 also provides a detailed breakdown of RDTE costs at vehicle level taking into account airframe and engines integration costs. Moreover, as far as Production cost is concerned, Table 1 provides TFU costs: by applying a proper learning curve factor as described in [1] and assuming a certain number of units produced, it is possible to derive total production costs for the vehicle. In addition, Table 2 shows results for Operating Costs. It is specified that Vehicle Recurring Cost (VRC) includes Production Cost Amortization and Refurbishment, while Cost per Flight (CpF) is defined as the sum of DOC, IOC and VRC. Eventually, Figure 4 provides a detailed breakdown of DOC, highlighting the contribution of operating cost items involved. From the CpF result provided in Table 2 and assuming a payload of 29,000 kg, a Cost/kg of 2,682 €/flight is calculated. The latter is in line with projected costs per kg for future RLV which shall be in the order of magnitude of 1,000 $/kg.

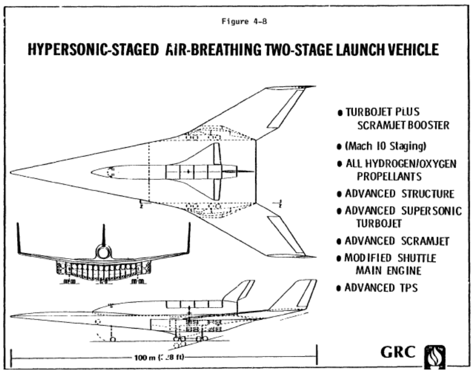


Figure 3: Airbreathing TSTO Vehicle analysed for Case Study 3 [9]

Cost Item	Cost [M€ FY2021]
Booster Airframe RDTE	43,134
Orbiter Airframe RDTE	17,378
Turbojet Engine (installed on Booster) RDTE	6,924
Scramjet Engine (installed on Booster) RDTE	7,523
Modified SSME (installed on Orbiter) RDTE	1,052
TSTO-AB Total RDTE	82,214
Booster Airframe TFU Production	2,894
Orbiter Airframe TFU Production	1,975
Turbojet Engine (installed on Booster) TFU Production	89
Scramjet Engine (installed on Booster) TFU Production	47
Modified SSME (installed on Orbiter) TFU Production	99
TSTO-AB Total TFU Production	5,905

Table 1: RDTE and Production Cost Results for TSTO-AB Vehicle

Cost Item	Cost per Flight [M€ FY2021]
DOC	38.61
IOC	4.66
VRC	34.49
CpF	77.77

Table 2: Operating Cost Results for TSTO-AB Vehicle

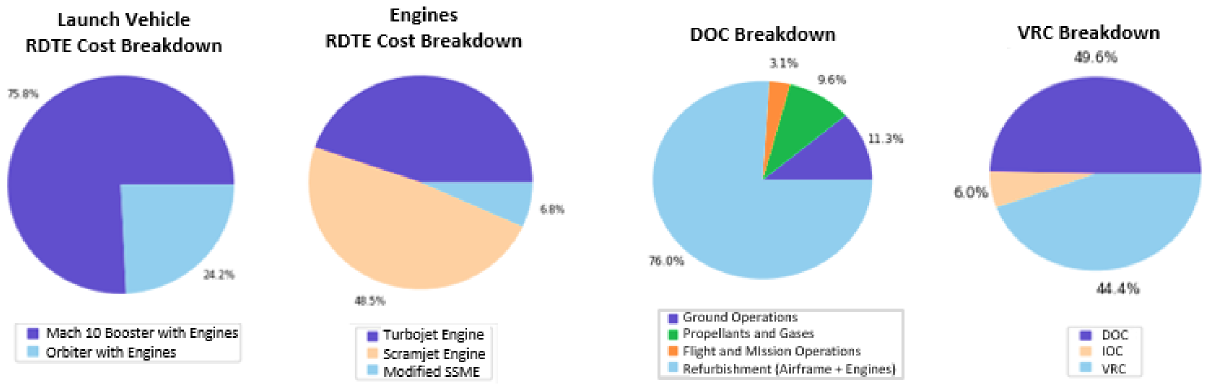


Figure 4: TSTO-AB Costs Summary

5 CONCLUSIONS

This paper has presented a methodology to assess LCC for future reusable access to space vehicles since the early conceptual design stages. In particular, starting from the equations reported in TransCost methodology, a new set of CERs has been developed in order to assess the impact of different RLV design solutions onto costs. Moreover, thanks to a selected TSTO case study, it has been possible to verify the effective potential or future RLVs to reduce launch costs.

6 ACKNOWLEDGEMENTS

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