Exploring the Feasibility of Single-Stage-To-Orbit (SSTO) Vehicles through Theoretical Analysis

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Abstract

The concept of Single-Stage-to-Orbit (SSTO) launch vehicles presents a potential revolutionary shift in how space can be accessed by removing the need for multistage rockets. This research takes a close look at the technical challenges that have prevented SSTO launch vehicles from becoming a reality. These challenges include propulsion limitations, mass and energy constraints, and re-entry system requirements that will be explored using theoretical modeling and comparative analysis. Through this theoretical modeling and comparative analysis, the research will evaluate if the advancements that have occurred in propulsion technologies and materials science can make SSTO launch vehicles a realistic capability to replace multistage rockets. Through the simulations that are a part of this research and case studies that include the Delta Clipper - Experimental and Skylon, a comparison of SSTO launch vehicle designs will be compared with multistage rocket systems in terms of cost, efficiency, and reusability. The goal of this research is to understand where SSTO launch vehicle technology stands today and if the technology that exists today can support them technically and economically.

Keywords: Single-Stage-to-Orbit (SSTO), launch vehicles, SSTO, SSTO launch vehicles, theoretical modeling and comparative analysis

Exploración de la viabilidad de los vehículos de una sola etapa a la órbita (SSTO) mediante análisis teórico

Resumen

El concepto de vehículos de lanzamiento de una sola etapa a la órbita (SSTO) presenta un cambio potencialmente revolucionario en el acceso al espacio, al eliminar la necesidad de cohetes multieta-

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pa. Esta investigación analiza en detalle los desafíos técnicos que han impedido que los vehículos de lanzamiento SSTO se hagan realidad. Estos desafíos incluyen limitaciones de propulsión, restricciones de masa y energía, y requisitos del sistema de reentrada, que se explorarán mediante modelos teóricos y análisis comparativos. Mediante estos modelos teóricos y análisis comparativos, la investigación evaluará si los avances en tecnologías de propulsión y ciencia de materiales pueden convertir a los vehículos de lanzamiento SSTO en una alternativa viable a los cohetes multietapa. Mediante las simulaciones que forman parte de esta investigación y estudios de caso que incluyen el Delta Clipper - Experimental y el Skylon, se compararán los diseños de vehículos de lanzamiento SSTO con los sistemas de cohetes multietapa en términos de costo, eficiencia y reutilización. El objetivo de esta investigación es comprender la situación actual de la tecnología de vehículos de lanzamiento SSTO y si la tecnología actual puede respaldarla técnica y económicamente.

Palabras clave: Vehículos de lanzamiento de una sola etapa a órbita (SSTO), modelos teóricos y análisis comparativo

通过理论分析探究单级入轨（SSTO）飞行器的可行性

摘要

单级入轨（SSTO）运载火箭的概念有望彻底改变太空进入方式，摆脱对多级火箭的依赖。本研究深入探讨了一系列阻碍SSTO运载火箭实现的技术挑战。这些挑战包括推进系统限制、质量和能量约束以及再入系统要求，本文将运用理论建模和比较分析方法进行研究。通过这些理论建模和比较分析，本研究将评估“推进技术和材料科学的进步”是否能够使SSTO运载火箭成为替代多级火箭的现实选择。本研究将通过仿真以及包括Delta Clipper实验型和Skylon在内的案例研究，从成本、效率和可重复使用性等方面对SSTO运载火箭设计与多级火箭系统进行比较。本研究的目标是了解SSTO运载火箭技术的现状，以及现有技术是否能够在技术和经济上为其提供支持。

关键词：单级入轨，运载火箭，SSTO，SSTO运载火箭，理论建模与比较分析

Introduction

Single-Stage-to-Orbit (SSTO) launch vehicles have been pursued for decades to simplify access to space by removing staging. Unlike reusable multistage rockets such as Falcon 9, which revolutionized launch economics, an SSTO would eliminate staging altogether and could further reduce cost and complexity. SSTO concepts such as McDonnell Douglas's DC-X, Lockheed Martin's VentureStar, and Reaction Engines' Skylon show both the promise and challenges of this approach.

Early Recognition of SSTO Possibilities

While NASA developed the Space Shuttle in the 1970s, studies also explored what a next-generation orbital system might look like. A 1977 report prepared for NASA (Haefeli et al., 1977) concluded that a fully reusable SSTO vehicle with horizontal landing was the most promising long-term approach. The report highlighted the need for projected advances in thermal protection systems, lightweight composites, and higher-efficiency propulsion to make SSTO viable. Although these improvements were never fully realized, the study helped shape subsequent SSTO efforts such as DC-X, VentureStar, and Skylon.

Fundamentals of SSTO Mechanics

Reaching a 400 km low Earth orbit requires ~9.3–9.5 km/s of delta-v, making mass ratio the defining challenge. Using the Tsiolkovsky equation, a Falcon 9 achieves orbit in two stages with an effective mass ratio of ~17. A hypothetical SSTO with advanced propulsion would need a mass ratio of ~8.3 in a single structure, implying a dry mass under 12% of liftoff weight—a difficult but theoretically possible target.

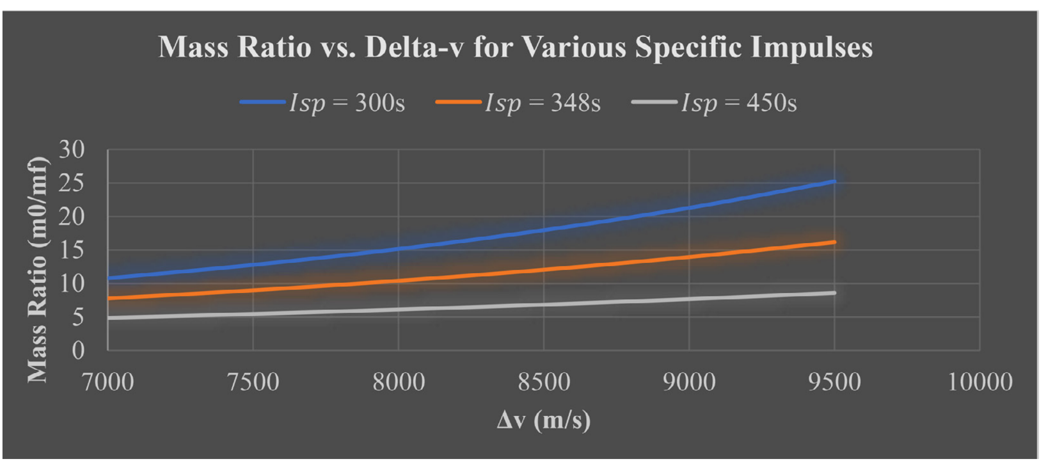

Figure 1. *Graph of mass ratio vs. delta-v for SSTO vs. multistage rocket.*

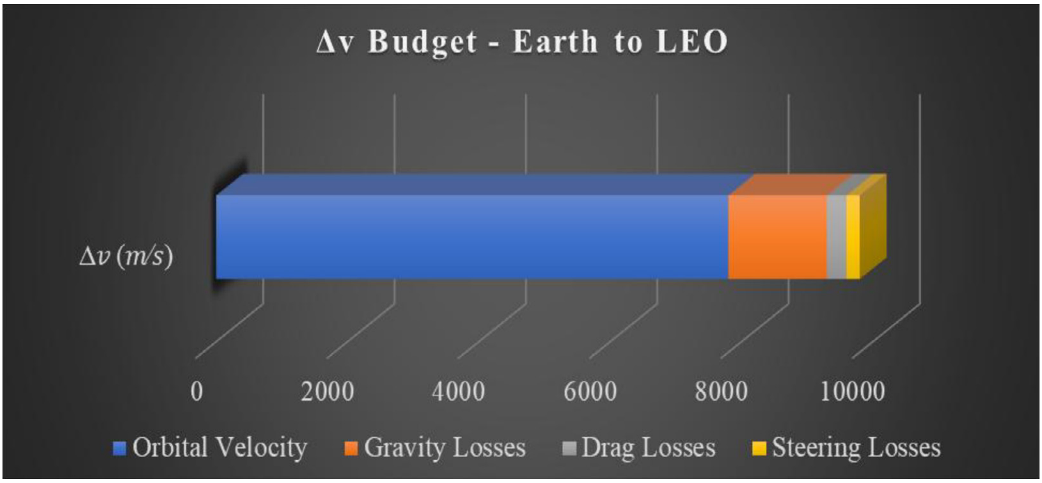

Figure 2. Annotated delta-v budget for Earth-to-LEO.

Propulsion Systems for SSTO

Conventional rocket engines cannot reach orbit in one stage due to limited specific impulse (300–450 s). Combined-cycle propulsion concepts such as Rocket-Based Combined Cycle (RBCC) and the Synergetic Air-Breathing Rocket Engine (SABRE) offer higher efficiency by using atmospheric oxygen during ascent. SABRE, for example, transitions from air-breathing to rocket mode at Mach 5 and could deliver Isp values sufficient for SSTO. While thermal management remains a hurdle, these systems are the most credible enablers of SSTO.

Mass and Energy Budget Considerations

Traditional rocket-based SSTO concepts require propellant fractions as high as 87%, leaving little room for structure or payload. By contrast, SABRE and RBCC engines reduce propellant fractions to ~76–81%, enabling lighter structures and reusable thermal protection. The trade-off is greater complexity in managing transition phases and thermal loads.

Case Studies

Delta Clipper Experimental (DC-X)

The DC-X, developed by McDonnell Douglas in the 1990s, demonstrated rapid turnaround and autonomous vertical takeoff/landing, though it never reached orbit.

Venture Star (X-33)

Lockheed Martin's X-33 aimed to validate advanced materials and lifting-body SSTO design but was canceled in 2001 due to composite tank failures

Skylon

The Skylon SSTO vehicle uses SABRE propulsion technology developed by Reaction Engines Limited and is the most recent SSTO concept in development. The combined cycle engine operates as both an air-breathing jet as well

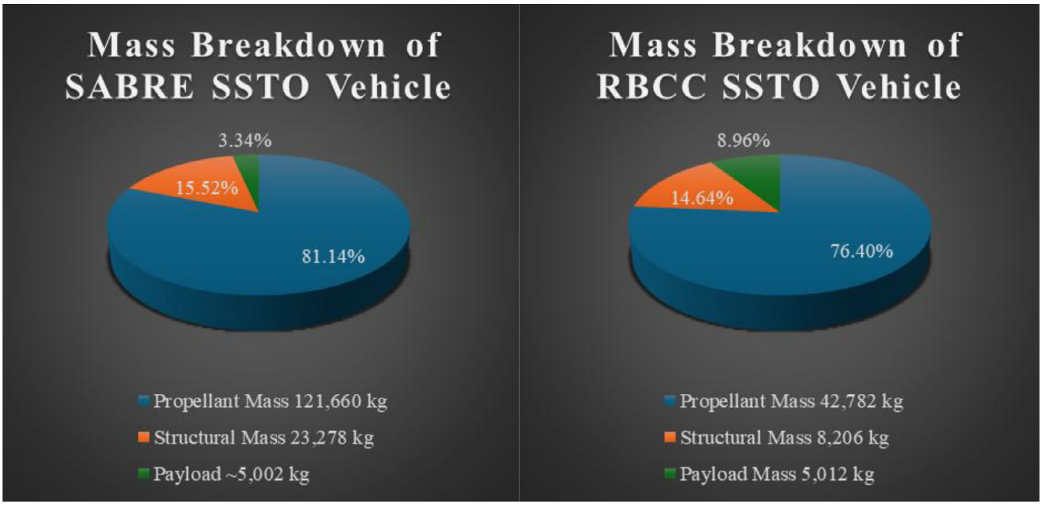

Figure 3. *Pie charts breaking down mass of SABRE and RBCC SSTO launch vehicles.*

as a close cycle rocket. The combined cycle capability reduces the oxidizer requirement, resulting in a much lower take-off mass. Skylon is designed as an unmanned, runway-launched SSTO with a 15-ton payload capacity to LEO. The UK government has evaluated the Skylon and has determined that the SABRE engine was technically feasible, and ground tests demonstrated successful operation of its precooler and core components (Scheidlinger et al., 2023).

Feasibility Outlook

Key subsystems of SSTO concepts have now reached TRL 5–7, with Skylon's SABRE engine validated through ground tests. Near-term feasibility rests on advancing TPS reusability and subsystem integration, while long-term viability requires continued investment in air-breathing propulsion and lightweight structural materials. Table 4 summarizes the comparative feasibility of major SSTO efforts.

Table 1. *Feasibility Matrix: SSTO Concept Evaluation.*

SSTO Concept	TRL	Cost Efficiency Potential	Reusability Potential	Current Status / Risk
DC-X	TRL 5–6 (demonstrated vertical landing)	Low – early prototype, limited scaling	Medium – limited to suborbital demo	Retired; influenced later designs like Falcon 9
X-33 / VentureStar	TRL 4–5 (partial subsystem demos)	Medium – aimed for cost reduction but faced structural issues	High – full reusability was the goal	Cancelled; failure of composite tanks
Skylon	TRL 6–7 (SABRE precooler tested; other subsystems validated)	High – reduced infrastructure and turnaround time	Very High – full-body reuse planned	In development; dependent on SABRE full engine validation

Conclusion

This research explored the technical and operational challenges surrounding SSTO vehicle feasibility. Through examining past and present case studies of X-33, DC-X, and Skylon, it has been determined that to overcome the mass, thermal, and propulsion constraints that define SSTO viability, additional development will be required. Comparative analysis with multistage rockets such as Falcon 9 illustrated both the performance limitations and the potential long-term cost and operability advantages of SSTO architectures.

While SSTO vehicles remain technologically ambitious, recent advances suggest that limited operational roles, such as small payload delivery, reconnaissance, or rapid-response launches may soon be within reach. For commercial space sectors, SSTO vehicles offer the potential for high-frequency, low-maintenance missions once structural, and TPS material reusability issues are solved. For defense applications, they represent a strategic asset capable of launching on-demand with minimal ground infrastructure.

In conclusion, SSTO systems are no longer purely theoretical. With sustained investment, targeted research and development, and phased approach to prototyping, they may soon complement or even challenge the dominance of multistage launch vehicles in the evolving landscape of space access.

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