ABSTRACT

Title of Document: **COMPARATIVE SYSTEM ANALYSIS OF REUSABLE ROCKET AND AIR-BREATHING LAUNCH VEHICLES**

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A conceptual system design study was performed to assess and compare the parameters of single- and two-stage reusable air-breathing and rocket launch vehicles to identify configurations which improve space access and merit further developmental emphasis. Investigated air-breathing configurations included both two-dimensional and inward-turning inlet geometries and horizontal and vertical takeoff modes utilizing rocket or turbine engines. The baseline payload requirement was 20,000 lb to low-Earth orbit. The vehicles were evaluated utilizing several figures of merit including empty weight, wetted area, and maintenance hours. A further weight growth assessment ascertained the growth factor which characterizes each system's

design risk and growth response to technological uncertainty. An additional trade study investigated payloads up to 70,000 lb. The two-stage rocket results showed strong performance in applied metrics. Horizontal takeoff single- and two-stage air-breathers trailed far behind, while the vertical takeoff air-breathers were very competitive and merit further attention.

COMPARATIVE SYSTEM ANALYSIS OF REUSABLE ROCKET AND AIR-BREATHING LAUNCH VEHICLES

By

Adam F. Dissel

Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
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Dedication

To my incredible parents Frederik and Karen who have always encouraged me to reach for the stars. To my brothers Andrew and Jonathan and sister Sofia; who are my best friends in the world and always humored me when I woke them in the middle of the night to go out and watch the stars. To my friend and mentor John Barainca for exemplifying the role of a true teacher. To my sons Caleb and Seth for always being excited to see their papa's rockets and keep me in their prayers. And most importantly, to Elizabeth, my true love and eternal companion who blesses the lives of all she encounters and has made all my dreams a reality.

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Chapter 1. Introduction

1.1. *Motivation*

The rapid pace of launch vehicle development and improvement that characterized the industry in its early days has slowed greatly in recent years. The cost and preparation time required for space access has changed little since the first flight of the Space Shuttle in 1981. The partially-reusable Shuttle failed to deliver the drastic reduction in cost and turn-time that was expected. Current EELV systems make moderate improvements but are still completely expendable systems that require months of lead time per mission. Both the Air Force and NASA are interested in responsive, low-cost space access to support their respective strategic and exploration missions. The development of an advanced reusable launch vehicle (RLV) that can actually be simply operated and easily maintained would be a promising solution to meet the launch needs of the future. However, in the absence of greatly improved technology or correspondingly reduced turn-around time and cost, an RLV vehicle might not actually make any improvements over current EELVs. An RLV program should build upon the advances of previous programs without repeating their pitfalls. Having pushed rocket propulsion technology close to its theoretical maximum, technological advances are required in other areas to improve the capability of an RLV. One well-researched technology that may find successful application is the use of air-breathing engines for some or nearly all of the flight to orbit.

1.2. Air-Breathing Justification

1.2.1. Air-Breathing Advantages

The principal benefit of a high speed air-breathing engine is that the oxidizer required for combustion can be obtained from the ambient air and need not be carried by the vehicle, as must be done with a conventional rocket. Oxidizer can compose nearly half of the liftoff weight of a typical rocket vehicle. The use of a hypersonic air-breathing ramjet/scramjet[1] engine eliminates the need to carry that oxidizer for that portion of its ascent trajectory. This weight savings can have very pronounced beneficial impacts on the scaling behavior of a vehicle system and results in a vehicle with a smaller gross weight. The performance gain also enables the solution of SSTO vehicles that exhibit greatly reduced weight and scaling behavior versus SSTO rockets. The elimination of extra stages and the reduction in vehicle mass suggest that an air-breathing SSTO air-breathing vehicle might be superior to multi-staged rockets in terms of operational and refurbishment costs while increasing the flight rate.

1.2.2. Air-Breathing Disadvantages

The nature of high-speed flight within the Earth's atmosphere raises a list of well-established design challenges that must be properly considered in order to fairly assess the advantages and disadvantages of air-breathing versus traditional rocket engines. Indeed, a scramjet-powered launch vehicle would still require rocket power for the final part of its ascent trajectory outside of the Earth's atmosphere, and would also require some additional engine or cycle component for low-speed flight. Options for this low-speed propulsion might include turbine or rocket engines, or the use of booster rocket or high-speed carrier aircraft. The atmospheric ascent also penalizes the vehicle with increased heating issues and drag losses versus typical rockets.

1.3. Previous Work

The last few decades have witnessed a multitude of proposed reusable launch vehicles combining many different configurations, operations, and propulsion technologies in an attempt to improve the costs and reliability of future generation systems. Several of the designs progressed from paper studies into sub-scale experimental vehicles before being cancelled. The Space Shuttle, while only partially reusable, is the only program that resulted in an operational launch vehicle. A brief overview of the most notable RLV programs is presented below:

1.3.1. X-20 Dyna-Soar

The X-20 was a 1960's Air Force program[2] to develop a reusable spaceplane that could be used for various military missions. The configuration included a 35 ft long manned spaceplane carried aloft by expendable rocket stages (Figure 1.1).

Figure 1.1 Dyna-Soar and Expendable Upper-Stage (Artist's Concept[3])

The X-20 design was rocket powered and was among the first vehicles to incorporate hypersonic design features[4] such as highly swept wings with blunted leading edges and a blunt-nosed fuselage, features that would later be used for the Space Shuttle Orbiter. The program faced difficulties adapting to ever-changing redefinitions of its mission from space bomber to test aircraft to reconnaissance platform. The project was cancelled in 1963 after which the Air Force pursued several different reusable spaceplane concepts before being becoming involved in NASA's Space Shuttle program in the 1970's.

1.3.2. Space Shuttle

The Space Transportation System (STS) effort began in 1972 with the goal of developing a reusable space launcher that would drastically lower the flight cost of space payloads. The Space Shuttle[5] is likely the most recognized spacecraft in the world and consists of a reusable rocket orbiter atop an expendable propellant tank and two solid rocket motors (Figure 1.2).

Figure 1.2 Space Shuttle Columbia at Liftoff[6]

The Shuttle was a joint program between NASA and Air Force and was designed to meet operational requirements of both entities. The Shuttle would therefore be capable of launching both military and commercial payloads. The Shuttle development was plagued by cost overruns and delays and the Orbiter came in overweight. The high cost of TPS and engine maintenance has resulted in multi-month processing flows of each Shuttle flight. The promised cost-savings and flight rate never materialized. The Shuttle has served as a large payload workhouse throughout its lifetime and has played key roles in the deployment of assets such as the Hubble Telescope and in the construction of the International Space Station (ISS). The Space Shuttle has launched 113 times and experienced two catastrophic failures; Challenger in 1986, and Columbia in 2003. After a two-year review, the Shuttle is scheduled to return to flight in the summer of 2005 to resume ISS assembly flights and is slated for retirement in 2010.

1.3.3. X-30 National Aerospace Plane (NASP)

The X-30 National Aerospace Plane (NASP)[7], Figure 1.3, was a program begun during the Reagan administration to design and construct a hypersonic air-breathing SSTO vehicle that would takeoff and land like an airplane.

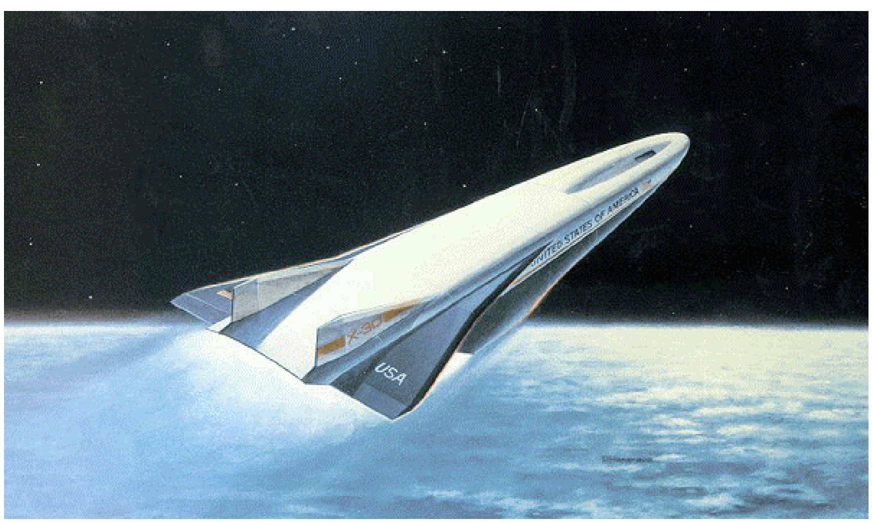


Figure 1.3 National Aerospace Plane (Artist's Concept[8])

The NASP Joint Program Office was formed in 1986. The NASP vehicle consisted of a wedge-shaped lifting body fuselage with small wings, and employed several ventrally mounted scramjet engines as well as ascent rockets. It was estimated that NASP would be approximately 200 ft long and weigh 300,000 lb at liftoff. NASP funding reached a peak in 1989, spending over $300 million. Mounting technical challenges continued to inflate the program cost which, in 1992, was estimated at $15 billion. The high cost and technological immaturity of the project let to its restructuring, and then eventual cancellation in 1994. A success of the NASP program was the increased level of hypersonic technology that resulted from the effort, much of which directly contributed to the later success of the X-43 flight test program.

1.3.4. Delta Clipper Experimental (DC-X)

The Delta Clipper Experimental[9], shown in Figure 1.4, was a vertical-takeoff, vertical landing (VTOL) rocket test vehicle sized to be one-third the size of an eventual SSTO rocket launch vehicle.

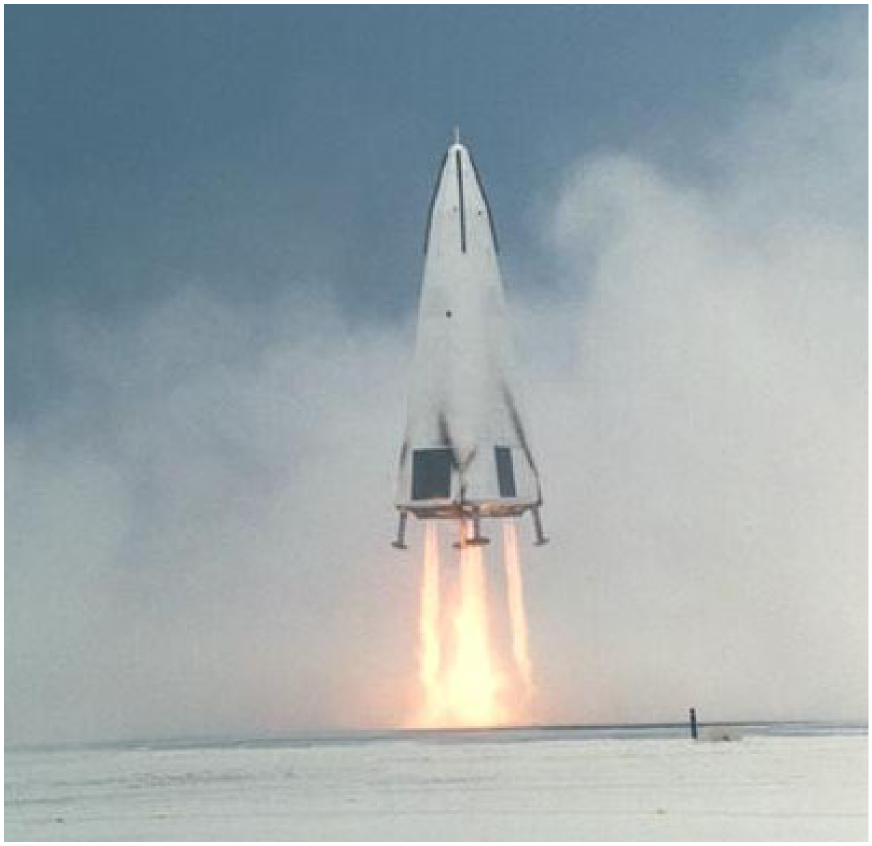


Figure 1.4 DCX Performing Vertical Landing[9]

McDonnell Douglas began construction of the DC-X in 1991 and the first flight was in August of 1993. By July of 1995, the DC-X had performed 8 flights which checked out various vehicle systems such as flight control, ascent and landing control, autoland, and roll and pitch maneuvers. The Delta Clipper Experimental Advanced (DC-XA) was a modified version of the DC-X and incorporated several weight-saving modifications such as a graphite-epoxy liquid hydrogen tank, and aluminum-lithium liquid oxygen tank. The DC-XA was run by NASA and the Department of Defense as part of the Reusable Launch Vehicle program. The DC-XA was flown four times out of White Sands. On its third flight, the vehicle demonstrated the ability to do a 26-hour turn-time. Unfortunately, the DC-XA was destroyed when on of its landing struts failed to deploy causing the vehicle to tip over and the LOX tank to explode. The cause of the failure was determined to be an unconnected helium pressurant line which provided hydraulic pressure to deploy the strut. The Delta Clipper Experiment made solid progress in proving the possible operation of a VTOL vehicle. Regardless of takeoff mode, it also demonstrated the possibility for the fast turn-around of a reusable rocket vehicle, though the vehicle was subscale.

1.3.5. X-33 RLV Prototype

The X-33[10] was another subscale SSTO rocket vehicle program. Announced in 1996, the X-33, shown in Figure 1.5, was developed in partnership with Lockheed Martin as part of the Space Launch Initiative.

Figure 1.5 X-33 Prototype (Artist's Concept[11])

Lockheed's VTHL design was chosen above competitors McDonnell Douglas and Rockwell but won out with its lifting body design and incorporation of promising advanced technologies[12] including composite fuel tanks, an integrated TPS system, and linear aerospike rocket engines. The X-33 also was intended to demonstrate improved serviceability and low-cost maintenance. If successful, the subscale X-33 would lead the way for the development of a full-scale SSTO rocket, the VentureStar, which was intended to provide a Space Shuttle replacement vehicle in the 2010 timeframe. The X-33 was delayed due to issues in the development of the aerospike engines as well as the TPS and control systems. However, the real difficulty was the failure in the abilities of the composite fuel tanks.

Concluding that the project relied to heavily on unproven technologies, NASA cancelled the program in March 2001. The spacecraft was approximately 75% complete at its termination.

1.3.6. X-43A Scramjet Experiment

NASA has recently achieved several important milestones in the development of hypersonic air-breathing technologies with the successful flights of its X-43A vehicle built by MicroCraft. The project serves as a test-bed to prove and flight validate key propulsion and system technologies required for future scramjet vehicles. The X-43A vehicle is 12 ft long and 3 ft wide and is carried to scramjet start by a modified Pegasus rocket booster, Figure 1.6, which is carried aloft and air-launched from a B-52, Figure 1.7, from NASA Dryden in California.

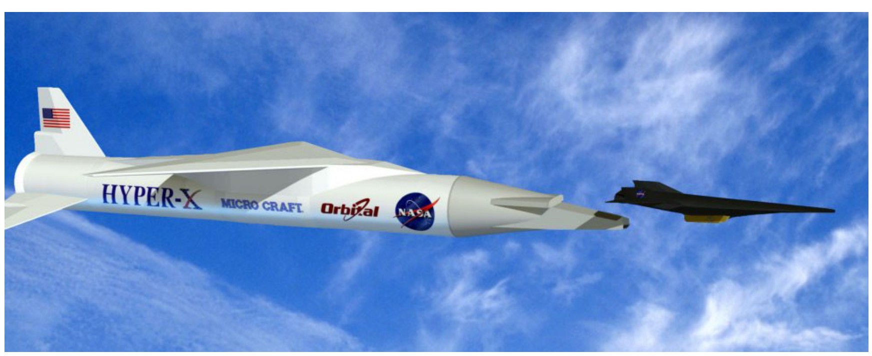


Figure 1.6 X-43A Separation from Pegasus Booster (Artist's Concept[13])

Figure 1.7 X-43A Pre-flight Integration with Carrier Aircraft[13]

On its second flight attempt in March 2004, the X-43 set a new air-breathing speed record of Mach 6.8. On November 16, 2004, it broke its own record during its third flight achieving a speed of Mach 9.6. The X-43 flights provided the first handful of seconds of actual flight data during scramjet operation. The X-43A program ended with the Mach 10 flight attempt, but may be revived if funding is re-allocated. The successful flights of the X-43A provided the first reassurances that scramjets could be successfully utilized to propel high-speed aircraft in actual flight.

1.4. Research Objectives

This research work was undertaken with the goal of determining the impact of air-breathing scramjet technology on SSTO and TSTO vehicle configurations. Of primary interest is whether these configurations are capable of yielding the desired order of magnitude reduction in the cost and time of space access compared to existing launchers. The vehicle variations were chosen in order to understand the integrated effect of different choices of propellant loading, staging, and operational modes in a hypersonic space system. The study also sought to understand the influence of technology on these air-breathing vehicle solutions with the specific goal of identifying key technologies which, if improved, gave the greatest improvement to the vehicle solution; this information could then be utilized to focus developmental emphasis on the most enabling technologies. The air-breathing designs were compared against an advanced rocket baseline vehicle to determine their competitiveness. The large numbers of investigated configurations were also intended to provide a body of work that represented the available design space and that would be beneficial in making future decisions regarding the development of next-generation launch vehicles and in defining the best evolutionary path for hypersonic technology.

1.5. *Thesis Overview*

The results of this investigation are presented in eight chapters and several appendices. Chapter 2 outlines the methodology employed in this study including descriptions of the HySIDE design code and the figures of merit utilized in evaluating the studied vehicle systems. Chapter 3 provides a discussion of many of the vehicle considerations and subsystem assumptions which were needed to setup the solutions and to evaluate the results. Chapter 4 presents the system investigation of a TSTO next-generation fully-reusable rocket which served as the baseline vehicle by which to measure the differences in the solutions of the air-breathing vehicles. Chapter 5 presents the results of the SSTO HTHL and VTHL air-breathing vehicles that were considered. Chapter 6 analyzes three different TSTO configuration categories combining air-breathing and rocket vehicle stages and discusses the advantages of TSTO systems in achieving eventual SSTO systems. Chapter 7 contains a detailed weight growth study of all the vehicles and provides insight into why SSTO programs have failed in the past and which will be most likely to succeed in the future. Chapter 8 incorporates the addition of the maintenance man-hour figure of merit and performs a payload trade on selected configurations and compares them both against each other and existing launchers. Each of the above chapters contains a summary of the conclusions garnered from the work of that chapter. The overall conclusions and trends identified as a result of this work are summarized in Chapter 9.

Chapter 2. Methodology

2.1. Research Approach

Other configuration studies have been performed by industry on both similar and different launch vehicle configurations. These studies are often conducted internally or at the request of government entities. Given the state of competition extant in the aerospace industry, it is not surprising that when multiple companies pursue different designs from each other that each returns as a proponent of their own design. The current study assumes that an across the board study of different vehicle options analyzed through the consistent application of identical assumptions and methods performed by a single independent entity, would be of more value in understanding the nature of the design space than multiple, separate, and dissimilar single point designs. The present investigation is an effort to evenly view many of these possible configurations in as fair an "apples to apples" comparison as possible, subject to some reasonable assumptions and projections of available technology. The goal is not to provide final optimized designs, but rather to identify configurations that merit further development and which should be passed over. No conscious attempt has been made to advocate air-breathing vehicles over those that use purely rocket propulsion. A promising next-generation two-stage rocket configuration has been selected as the benchmark by which to evaluate any further advantages of developing the additional technology required for future air-breathing vehicles.

2.2. *Design Code*

All vehicles in this design study have been configured with the HySIDE[14] code developed by Astrox Corp. The code is a component-based object-oriented design package within a systems engineering software environment. HySIDE uses analytical solutions and tabulated data as available rather than detailed computational fluid dynamic solutions in order to be speedy and flexible while still maintaining a high degree of accuracy. Utilization of the code's rapid design and analysis capabilities allows for the quick systematic comparison of hundreds of design parameters and input cases.

To design a hypersonic vehicle, the code uses the freestream Mach number and altitude at a chosen design point and specified bow shock strength, from which the method of characteristics and streamline tracing methods[15] are used to form the inlet surface. After the trace, the surface inviscid forces are known as is the inlet exit flow state. A quasi-one-dimensional combustor model is used to model the mixing and burning of hydrogen or hydrocarbon, and a combustor surface is defined. The nozzle flow field is then also created using the method of characteristics. An external surface joins the inlet capture area and nozzle exit. A reference temperature method is then applied to determine the viscous forces, heat transfer, and boundary layer displacement thickness on each surface. The aerodynamic forces are determined by integrating the pressures on each surface's gridpoints[16]. A rocket vehicle is analyzed with the same methods, but without the internal flowpath surfaces.

The code has the ability to perform analysis in a completely integrated fashion (propulsion-airframe-massproperties-aero-gravloss-heating-volumes, etc). Individual components include either hypersonic air-breathing or rocket engines integrated into a full vehicle model; their performance is calculated over the complete mission trajectory. Vehicle sizing is done in an iterative loop. The vehicle is scaled until the volume available for the fuel is equal to the fuel volume needed based on individual component weights and densities. The code calculates the volumes and areas of all the components and from this subtracts the volumes of payload, equipment, TPS etc. The resulting volume is multiplied by a tank packaging efficiency as a measure of how well the tank shape is able to use the available volume. The resulting value is the volume available for propellant, and must equal the fuel volume required to complete the mission trajectory in order to “close” the vehicle. All of the components will require resizing as the vehicle is continuously scaled to match all of these requirements simultaneously.

The entire code consists of over 200 subroutines and functions that account for approximately 12,000 executable lines of code. Several standard codes, such as Missile Datcom for aerodynamics, have been integrated into the code’s suite of analysis tools. Set up time for the complete analysis of a new system requires several days and, once the included components of the specific vehicle system are connected, the system calculations for each solution run are done in about ten minutes on a standard desktop PC. The code has the ability to model 21 different commercially-available rocket engines as well as air-breathing scramjet-based engines and traditional turbine engines using a variety of inlet geometries. Rocket geometries are also included.

Appendix A contains screenshots showing the user interface as well as several hierarchal levels of system object components for a representative vehicle.

2.3. *Figures of Merit*

2.3.1. Empty Weight

At this level of analysis, the total vehicle system empty weight may be successfully employed as a main cost driver of a launch vehicle system. Most of the launch operation and flight refurbishment costs, as well as the initial design and procurement costs of a launch vehicle scale roughly with empty weight[17]. When comparing the empty weights as a rough measure of the approximate cost and feasibility of designing and constructing the vehicle[18] it must be remembered that, "pound for pound", a reusable rocket stage will almost certainly cost[12] more than an expendable rocket stage. Furthermore, a reusable upper-stage will likely cost more "pound for pound" than a reusable first stage.

2.3.2. Wetted Area

Another valuable figure of merit is the wetted area of the vehicle. The amount of wetted area impacts the vehicle's performance, weight, and operational cost. Specifically, the skin friction drag and TPS both scale with the wetted area of the vehicle. The reduction of TPS area yields a double benefit, the first being a reduction in weight, and second a reduction in the time and cost of TPS refurbishment. TPS maintenance is a huge part of the

Space Shuttle's between flight refurbishment costs. State of the art and future advanced passive TPS materials may require less maintenance than previous TPS materials. In the case of air-breathing hypersonic vehicles, it is also important to distinguish between wetted areas that are actively- versus passively-cooled.

2.3.3. Maintenance Man-Hours

The amount of maintenance man-hours[19] and refurbishment between flights of a reusable vehicle is a large part of the system's total lifetime cost. The lesson learned from the Shuttle program was meaningful cost reductions promised by the development of reusable vehicles are only achievable if the vehicle can be quickly and easily turned around for its next flight. Indeed, this is one of the prime reasons for a viable airline industry; the ability to do minimal maintenance between flights, and to do many flights before needing more significant maintenance. The largest maintenance items are the inspection and refurbishment of the TPS, engines, and fluid related subsystems such as the RCS, OMS, and APU. The maintenance cost of the TPS is primarily a function of the amount of wetted area covered and the type of TPS required. Engine maintenance scales with engine thrust while the fluid subsystems scale by number of thrusters or APUs utilized. Vehicles that may otherwise be comparable in empty weight and technology level may differ in terms of maintenance. The estimation and application of maintenance man hours is consequently a very practical and important system metric.

2.3.4. Gross Weight

Vehicle gross takeoff weight is often cited as a principle metric of comparison between different vehicle configurations. However, the vehicle gross weight is not as useful a figure of merit as the three listed above. The major constituents of the gross weight for the vehicles are the propellants required. Compared with the cost of acquiring, and maintaining the vehicle, the cost of purchasing each flight's propellant is nearly insignificant. While a higher gross weight vehicle for a given mission may represent a lower performing propulsion system, it is the impact of that performance on the vehicle's empty weight and surface area that are of the most interest. However, the gross weight was included in this study because it does give quick insight into the scaling of parameters that have to do with the fueled vehicle such as propulsion thrust requirement, and pad limitations. Also, for a multi-stage vehicle, the amount of gross weight of an upper-stage can greatly influence the sizing of the lower stage that carries it in which case an understanding of the gross weight sizing between different upper-stages is required to determine the resultant sizing of the booster.

Chapter 3. Vehicle System Considerations

3.1. *Reference Mission*

The reference mission was the delivery of 20,000 lb (9,070 kg) to a 100 nm (185 km) orbit. The vehicles were assumed to be launched easterly from Kennedy Space Center to a 50 nm by 100 nm transfer orbit and use OMS engines to circularize. The payload mass of 20,000 lb was assumed to include the associated mass of payload attachment fittings, shrouds, etc and can therefore be considered the mass of an integrated payload unit. A payload density of 7.08 lb/ft^3 (113.4 kg/m^3) determined as 40 m^3 per 10,000 lb was held constant for all solutions and payload trade studies. All the vehicles in this study were unmanned.

3.2. *State of the Art*

The reusable rocket boosters and orbiters included in this study have been selected to represent what was considered to be near-state-of-the-art rocket vehicles. The reusable rocket technologies and performance metrics were chosen to represent those that are available as of this writing.

By comparison, air-breathing scramjet technology is still maturing. The scramjet vehicle technologies assumed in this study were chosen to represent a reasonable extrapolation of the current technology. This extrapolation introduces more uncertainty into the air-breathing vehicle solutions than exists for the rocket vehicles. These enabling technologies primarily include: the actual Isp performance of a large-scale scramjet operating at higher Mach numbers and altitudes, the tank weight of conformal cryogenic tanks vs. standard cylindrical tanks, and the unit weights and temperature limits of both passive and actively cooled types of TPS. The estimates used for these parameters are believed to be realistically achievable without being overtly optimistic.

3.3. Operational Considerations

3.3.1. Trajectory Segments

A notable difference between the air-breathing and rocket vehicles are the different trajectories they fly as represented in Figure 3.1.

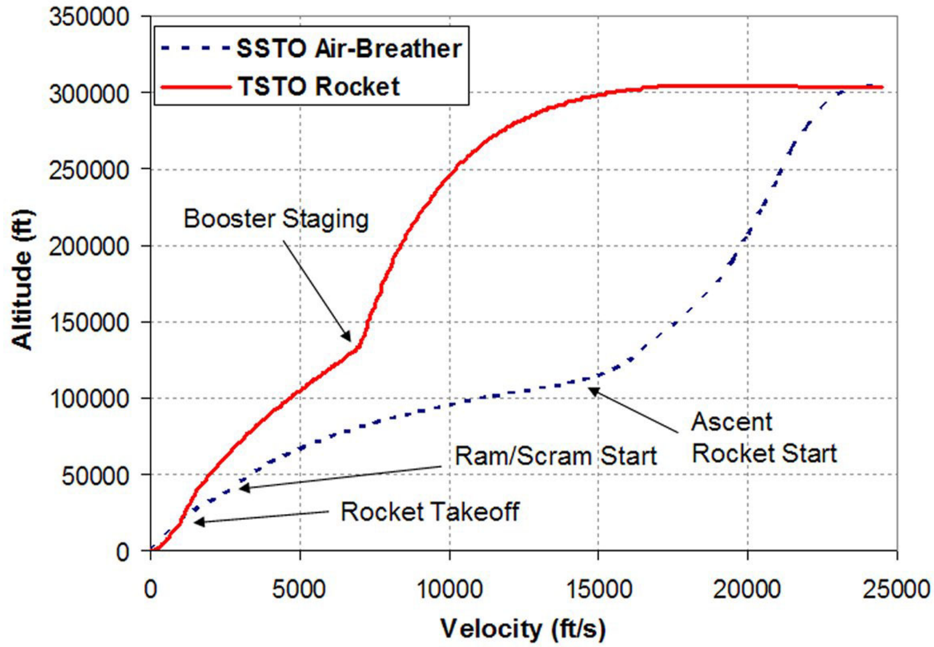


Figure 3.1 Ascent Trajectories: SSTO Air-Breather and TSTO Rocket

The trajectories for air-breathing SSTO vehicles are divided into three trajectory segments; launch and acceleration to ramjet starting point, ramjet/scramjet cruise to maximum scramjet Mach number, and the rocket ascent into orbit. These trajectory segments will be referred to as first, second, and third segments throughout the remainder of this work. The TSTO rockets are divided into two trajectory segments; one for the booster stage and one for the orbiter. For the rockets, the booster and orbiter segments are called first and third segments respectively; the second segment is reserved for a ram/scram segment if present and is not used otherwise. The TSTO air-breathers are done the same as SSTO air-breathers but with a staging event occurring either before the scramjet start or after the scramjet cutoff.

3.3.2. Horizontal vs. Vertical Takeoff

An ultimate goal of air-breathing configurations is to approach the same low cost and operational simplicity and flexibility enjoyed by other large air-breathing vehicles such as commercial airliners. To that end, many proposed[20, 21] air-breathing launch vehicles have been designed for horizontal takeoff and landing (representation shown in Figure 3.2.

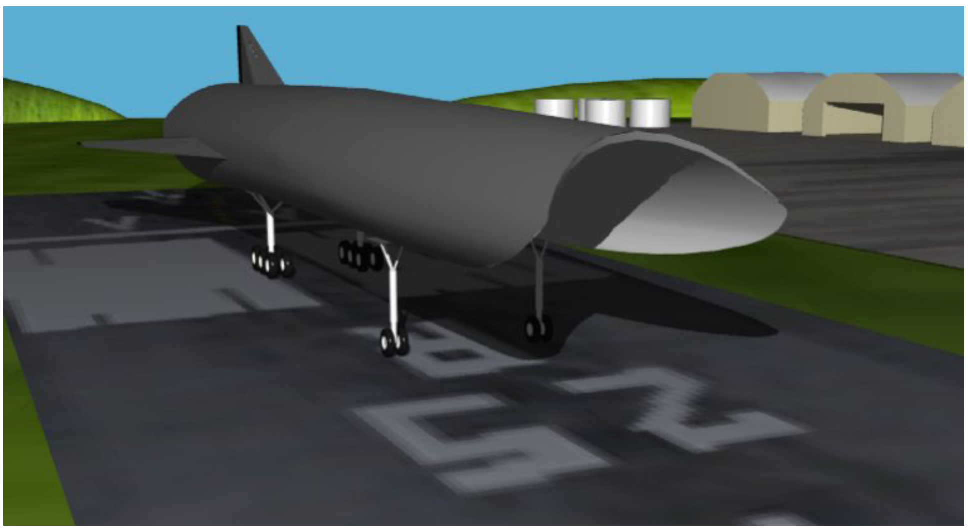


Figure 3.2 Horizontal Takeoff of Inward –Turning SSTO Air-Breather

It has been anticipated that an HTHL system would result in less support equipment, more frequent flight rates, and increased operational flexibility all of which would hopefully reduce the cost of an air-breathing launch vehicle over that of a more traditional VTHL rocket system. This expectation is partly based in the fact that HTHL aircraft, like jet airliners and military fighters, are historically much cheaper to operate than vertically launched rockets. One of the driving reasons that airplanes can be operated economically is that they require very little maintenance between every flight except for refueling. It must be remembered however, that an HTHL launch vehicle will never be a pure airplane. Whether vertically or horizontally launched, the vehicles will still have rockets and rocket propellant for ascent to orbit, reaction control and orbital maneuvering systems, passive and active TPS, and other systems in common. Just because the same horizontal launch mode as a traditional airplane is used for a spacecraft does not automatically bestow the economics of "airplane-like" operations on the vehicle configuration. Whether vertically or horizontally launched, "airplane-like" operations can only be achieved when the multiple and complex space vehicle systems are developed to approximately the same level of resiliency, maintainability, and reliability as current aircraft systems.

The traditional operational gap between vertical and horizontal operations tightens further now that horizontal integration, transportation, and assembly flow of vertically launched vehicles, such as the Sea-Launch Zenit-3SL, have been demonstrated. This processing and operations flow also eliminates the need for very "tall" structures such as a towering assembly buildings and gantry. The actual vertical operations for a VTHL vehicle may be reduced[12] to fueling and the launch itself. While both launch options imply the need for a certain amount of support hardware and personnel, it may be that the vertically-launched vehicle requires more of such resources, including some sort of erecting mechanism and launch pad (Figure 3.3) while the horizontal vehicle could use an airplane runway.

Figure 3.3 Vertical Takeoff Inward-Turning SSTO Air-Breather Lowered and Erected

Unlike an airliner however, an HTHL hypersonic launch vehicle will weigh approximately four times more at takeoff than it does at landing. The wings and landing gear must both be sized for the support of the larger gross weight instead of the much smaller empty weight plus payload weight, for which they are sized for the VTHL vehicle. If the HTHL vehicle is an SSTO, that extra launch weight must be carried all the way to orbit. On the other hand, VTHL vehicles must have takeoff rockets that are sized to provide thrust greater than weight, which means they will have a greater rocket propulsion mass to gross takeoff mass ratio than their horizontal-launch counterparts. Quantifying the trade-offs arising from the interactions of these different configuration parameters has been a principal goal of this investigation.

3.3.3. Takeoff and Landing Speed

Takeoff speed is one of the primary inputs into the sizing of the wings for an HTHL vehicle. An increase in the takeoff speed results in a smaller sized wing. Smaller wings are lighter, have less wetted area to cover in TPS, and impart a smaller drag penalty on the vehicle during later trajectory segments. The wing drag is especially important for the air-breathing vehicles as they spend substantial time in higher drag trajectories than the rockets. For this reason, many studies have assumed takeoff speeds higher than those used by existing large-scale aircraft. The HTHL vehicles in this study takeoff at about 225 knots (116 m/s) which is much higher than the 153 knots (79 m/s) takeoff of the Boeing 747 or even the 175 knots (90 m/s) takeoff of the supersonic Concorde. This higher speed helps relieve the wing problem significantly, and is believed to still be achievable from standard runways. Some other studies, noticing the scaling benefits, have investigated takeoff speeds as high as 300 knots (154 m/sec); roughly twice the speed of a jumbo jet takeoff at approximately the same gross weight! This type of takeoff, though beneficial to the performance of the vehicle, is likely to require a longer runway length, especially for abort scenarios, than is standard, thus eliminating one of the principal advantages of horizontal takeoff: operational flexibility. The runway length problem might be mitigated by not requiring the space vehicle to have the ability to brake to a stop in the event of propulsion loss during the takeoff run as is required of normal aircraft. However, if the space vehicle is not held to account in this regard then an engine loss during the takeoff could result in a loss-of-vehicle situation and remove the safety advantage in this particular area that horizontal takeoff vehicles have over verticals which always face the possibility of a vehicle loss if propulsion is lost during takeoff.

3.4. Propulsion Considerations

3.4.1. Inlet Geometry: Inward-Turning vs. 2D Flowpath

A hypersonic scramjet-powered vehicle is best thought of as a flying engine. The choice of the inlet type and combustor configuration will govern the entire vehicle geometry thus influencing not only the propulsive forces of the vehicle but also its aerodynamics, surface area, and volume. Two types of inlets are considered in this present work; the two-dimensional wedge and the three-dimensional inward-turning as represented in Figure 3.4.

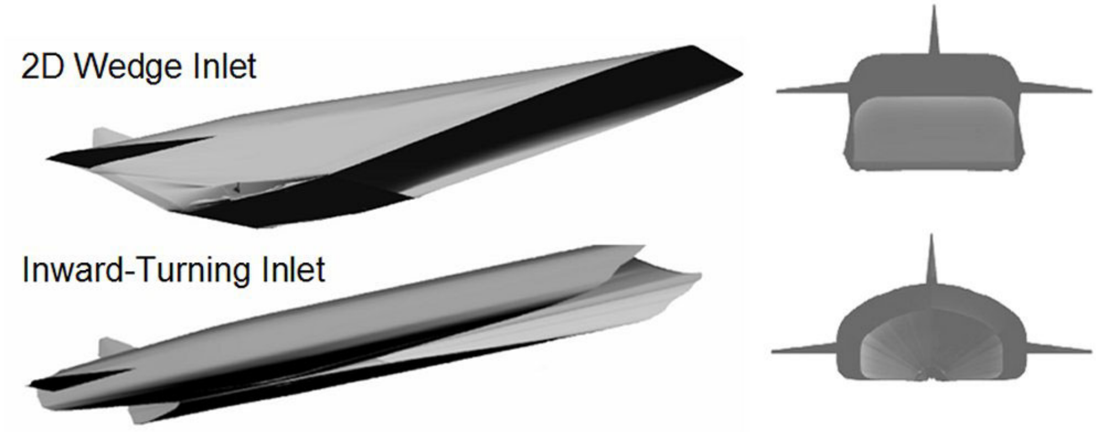


Figure 3.4 Inlet Geometries: 2D and Inward-Turning (perspective and front views)

The 2D wedge type inlet has been well researched in various forms for the last several decades. While not as well known, the possible performance gain of the inward-turning inlet has been bringing it more attention. The inward-turning geometry results in less wetted area in the high heating regions at the end of the inlet, through the combustor, and the entrance to the nozzle. The smaller wetted area yields an approximately 35% reduction in the amount of active cooling required by a similar 2D geometry, and a 50% reduction in heat transfer. The inward turning engine geometry has a single combustor flowpath which reduces the complexity and amount of actuators and seals compared to the 6-8 combustor flowpaths of the 2D vehicle. The reduced cooling loads and combustor provisions result in lighter engine and thermal protection weights. Additionally, the reduced viscous losses, smaller cooling requirements, and resulting increased heat balance velocity cause an increase in EISP enabling the inward-turning vehicle to reach a higher Mach number before scramjet cutoff. This behavior is evident in Figure 3.5 which compares two SSTO all-hydrogen fueled air-breathing vehicles; one with a 2D inlet and the other with an inward-turning inlet.

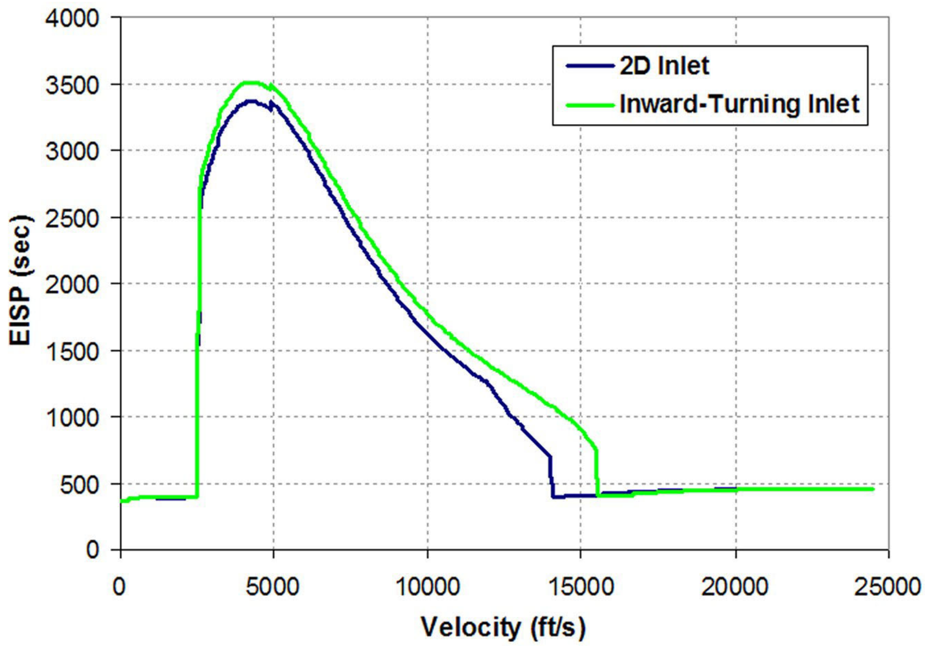


Figure 3.5 Effective Specific Impulse (EISP) Comparison: 2D and Inward-Turning

All of the above help to close the vehicle, in a synergistic way, at lower gross and empty weights than comparable 2D geometries. This study facilitates the quantification of these phenomena across different vehicle configurations. The heat transfer rates of the inward-turning and 2D inlet types at the scramjet design point are shown in Figure 3.6 and Figure 3.7 for the combined inlet-combustor-nozzle flowpath. Note the reduction in area and heat transfer rate that occurs for the inward-turning combustor.

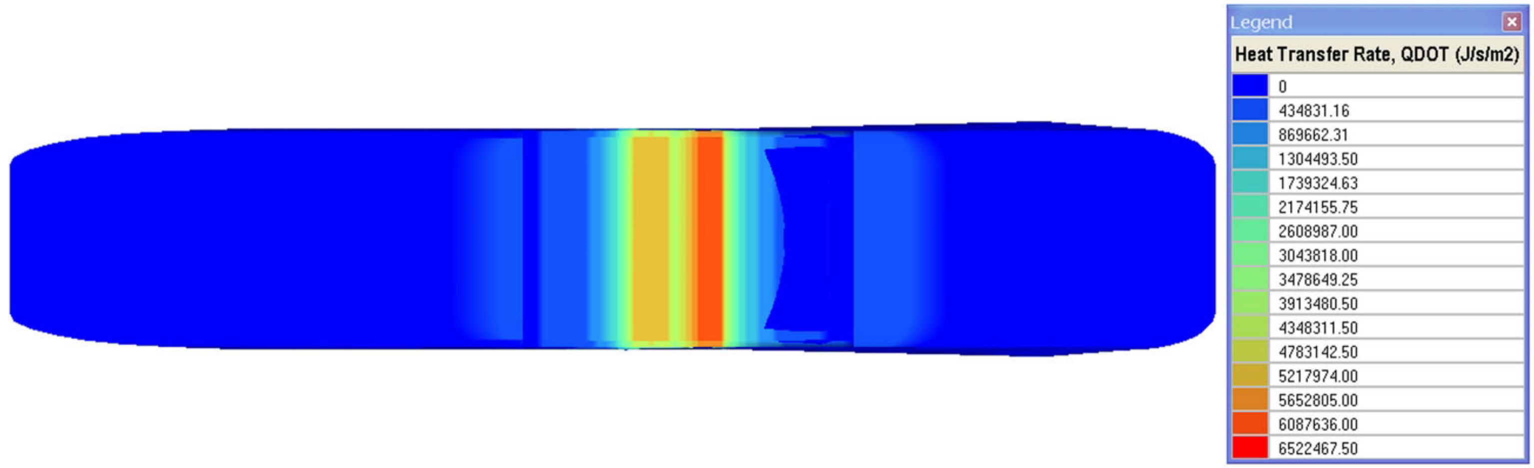


Figure 3.6 Heat Transfer Rate: 2D Flowpath

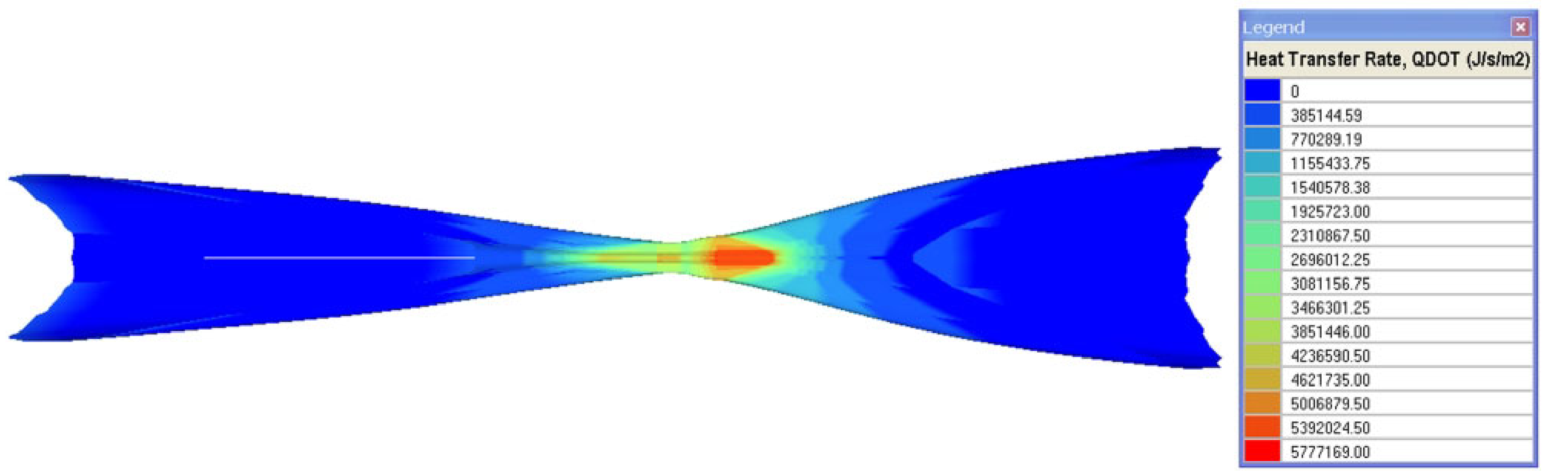


Figure 3.7 Heat Transfer Rate: Inward-Turning Flowpath

3.4.2. Propellant Selection

The tradeoffs in performance due to fuel selection are of particular note in this study. The design investigation considered two different fuels for each vehicle; liquid hydrogen and liquid hydrocarbon (RP-1 for rocket engines and JP-1 for turbines). The oxidizer for both fuels was liquid oxygen when under rocket powered flight. LH2/LOX offers the best Isp performance (~ 455 sec) of any of the typical rocket fuels; however, such performance comes at a cost. Though the high performance of hydrogen reduces the amount of propellant required, its very low density of 68 kg/m^3 requires an enormous volume to contain it, thus driving up tank and vehicle size and weight. Increased volume is tied to a corresponding increase in surface area, which imposes a further drag penalty during an air-breathing ascent trajectory. There is also a weight penalty from additional thermal protection acreage. Hydrocarbon fuel has a lower Isp (~ 330 sec) than hydrogen but is nearly twelve times as dense at 805 kg/m^3. Though more fuel mass is required to release the same propulsive energy, the high packing density of the hydrocarbon requires less volume. These phenomena have proven advantageous in studies[22] of hypersonic cruisers utilizing hydrogen or hydrocarbon propellants and are expected to be prominent in this study.

3.5. Structural Considerations

3.5.1. Passive Thermal Protection

High values of temperature and heat transfer are experienced by a vehicle during re-entry into the Earth's atmosphere. Hypersonic air-breathers have the additional heating challenge during their ramjet/scramjet ascent trajectories which are expected to be more severe than the re-entry environment[12]. Passive TPS systems protect the vehicle from these high heating environments by covering exposed areas with materials whose thermal properties enable them to withstand these environments and prevent heat damage to the rest of the vehicle. The Space Shuttle pioneered lightweight reusable TPS materials which replaced the ablative, one-time passive TPS of the Apollo capsules. The TPS materials used for the Shuttle tiles were silica fibers with a ceramic binder. Over 30,000 unique tiles covered a Shuttle Orbiter. Later, the lower temperature white tiles were replaced with an advanced fabric insulation that came in larger rigidized blankets. The temperature limits of these materials are listed in Table 3.1.

Table 3.1 Passive TPS Materials and Properties

	Max Temperature		Avg. Weight	
TPS	°F	K	lb/ft^2	kg/m^2
RCC	3000	1922	6.0	29.3
HRSI	2300	1533	2.0	9.8
LRSI	1200	922	1.0	4.9

Advancement of TPS technology is an ongoing task. Several new TPS types have been developed, such as TABI[20] and TUFI, which have temperature limits and unit weights similar to the black HRSI shuttle tile but are less fragile and easier to attach and maintain. The analysis code used for this study determines the surface temperatures over the entire surface of each vehicle analyzed. These temperatures were compared to the temperature limits in the table to determine the type of passive TPS required. Figure 3.8 and Figure 3.9 show the values of external surface and flowpath wall temperature for a 2D and inward-turning flowpath at their upper Mach number design points. As may be seen, the entire external surface of an air-breathing vehicle will require TPS protection. In viewing these figures, it is important to observe the mild temperatures seen in the bottom of the nozzle and throughout the combustor flowpath. These regions have severe heating environments, but the wall temperature in these areas are maintained relatively low due to the use of active cooling which will be discussed next.

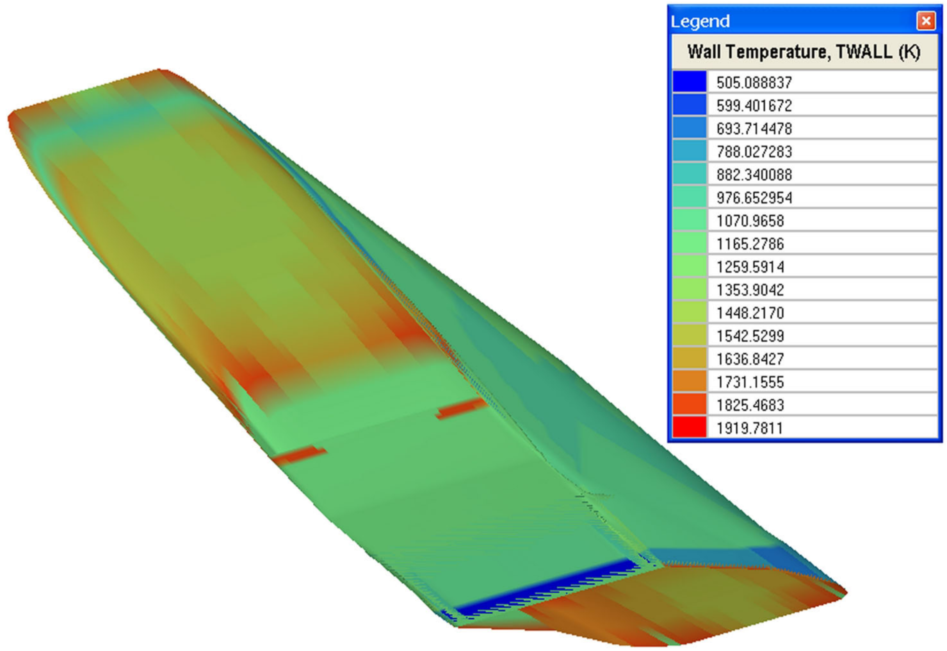


Figure 3.8 Fuselage and Flowpath Wall Temperatures for 2D Vehicle Geometry

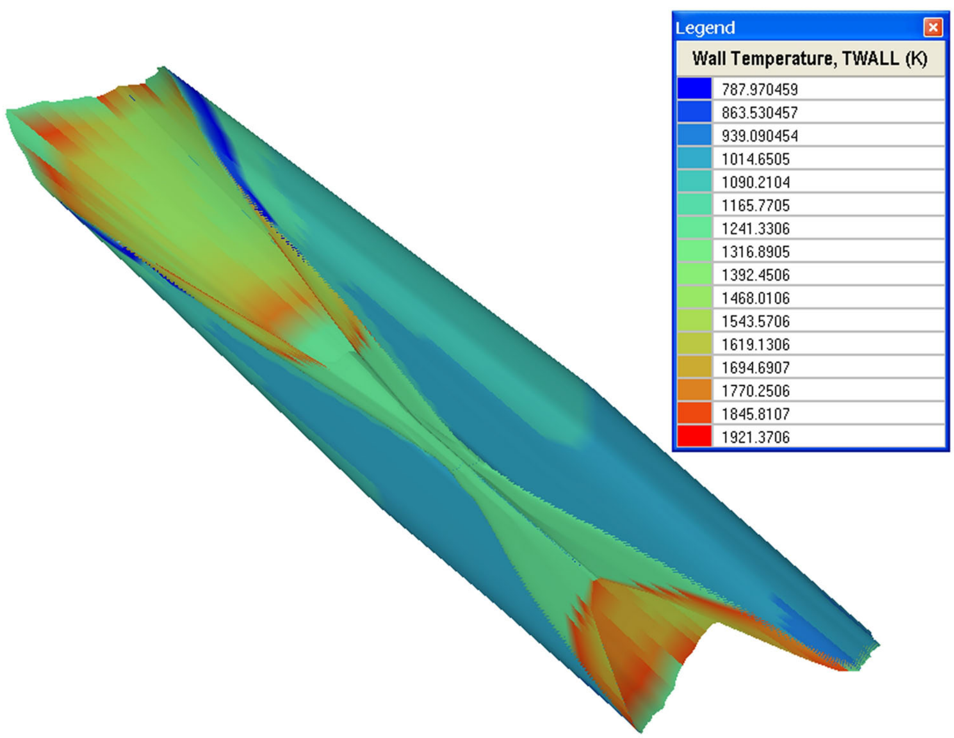


Figure 3.9 Fuselage and Flowpath Wall Temperatures for Inward-Turning Geometry

3.5.2. Active Thermal Protection

When the wall temperature of a surface exceeds the abilities of the most capable passive TPS used, then those areas must be actively cooled[23]. Actively cooled TPS consists of large metallic panels which are run as heat exchangers with liquid hydrogen as the working fluid. All of the air-breathers in this study use hydrogen for their ramjet/scramjet flight trajectories and operate their active TPS in a regenerative way similar to actively cooled rocket nozzles, though over much larger surface areas. The rocket vehicles in this study never require active cooling on their external surfaces and therefore have no fuselage active TPS, however they do have actively cooled nozzles on their rocket engines. The actively cooled TPS panels in this study were assumed to have a unit weight of 6 lb/ft^2 (29.3 kg/m^2) through the nozzle and inlet and a unit weight of 8 lb/ft^2 (39 kg/m^2) in the combustor. There is a great amount of uncertainty as to what the actual value of this weight parameter should be. The values chosen were seen as conservative. The large amount of active cooling areas on air-breathing vehicles provides a strong incentive for the reduction of active TPS unit weight. As mentioned in the inlet section, inward-turning inlets require much less active cooling than 2D inlets due to reduced surface area in the high heating regions. Figure 3.10 and Figure 3.11show the regions of active cooling for a 2D and inward-turning flowpath.

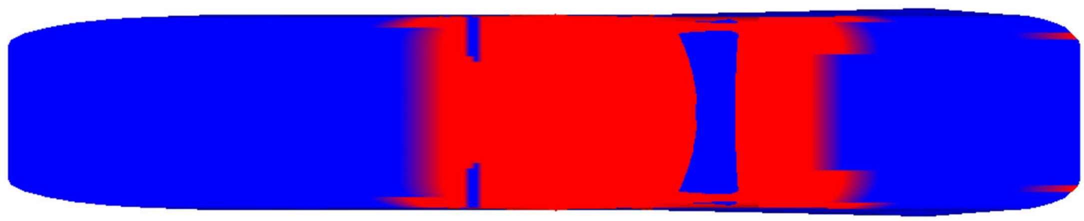


Figure 3.10 Active Cooling Regions for 2D Flowpath

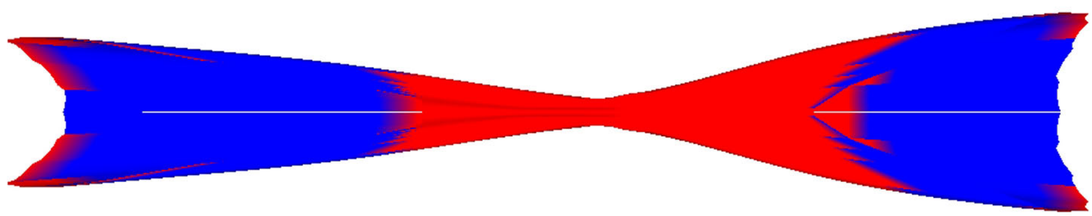


Figure 3.11 Active Cooling Regions for Inward-Turning Flowpath

3.5.3. Cylindrical vs. Conformal Tanks

Launch vehicles carry a large amount of fuel which, correspondingly, is carried in large propellant tanks. Tank weights are a very significant component in the sizing of the vehicle. Failure to accurately predict the resulting weight of the tanks could eliminate the vehicle's ability to perform its intended mission, as happened with the X-33 program. There is a great amount of experience in the design of standard cylindrical propellant tanks and typical rocket geometries are built around stacks of cylindrical fuel and

LOX tanks. Air-breathing geometries are much more complicated. To effectively package the required fuel inside the vehicle necessitates the use of conformal liquid hydrogen tanks. This is another technology in which there is a great amount of weight uncertainty. For the same volume, conformal tanks will be heavier than the more optimized spherical or cylindrical tank shapes; the difficulty is in determining how much heavier. The method used in this study was to compute the weight of a cylindrical cryogenic hydrogen tank for the fuel volume required and multiply that weight by a factor of 1.4. An additional uncertainty factor of 15% was also applied resulting in conformal hydrogen tanks that are 1.61 times as heavy as the same volume cylindrical tank. This value was considered achievable. Further advances would be quite beneficial.

3.5.4. Rocket Integration

The labeling of the hypersonic vehicles in this study as "air-breathers" merely distinguishes them from the purely rocket vehicles. Any hypersonic vehicle will require some use of rockets for the final ascent to orbit after scramjet cutoff. These rockets may also be used for takeoff and ascent propulsion until ramjet start. For this investigation the rockets were integrated into the hypersonic vehicle just downstream of the combustor in the first part of the scramjet nozzle. Figure 3.12 is a side perspective of this arrangement for an inward-turning geometry; 2D geometries were done similarly.

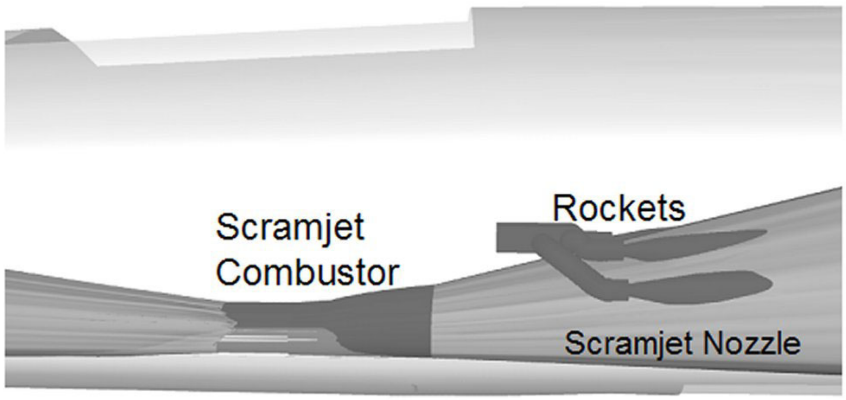


Figure 3.12 Ascent Rocket Integration within Hypersonic Nozzle (Side View Detail)

In the figure, the darker patches to the right are the rocket engines and the ram/scram combustor is the darker region to the left. This arrangement allows for the rockets to make use of the scramjet nozzle for additional expansion. The rocket nozzle ports are covered during ramjet / scramjet operation. This study did not examine any air-augmentation effect arising from the placement of the rocket engines. The rocket engines used were rubberized LH2/LOX Space Shuttle Main Engines[24] (SSME) or LHC/LOX RD-180 engines[25].

3.5.5. Turbine Integration

Integration of turbine engines into a hypersonic geometry is more of a challenge than the rockets. Unlike a rocket, the turbines require some kind of flowpath to provide them with a specified mass flow of air. This necessitates additional complexity and design considerations in the design of the inlet. Turbines also have a larger volume than a rocket at the same thrust level. The turbines in this study were assumed to be in an "over-under" configuration[26] above the scramjet as represented in Figure 3.13.

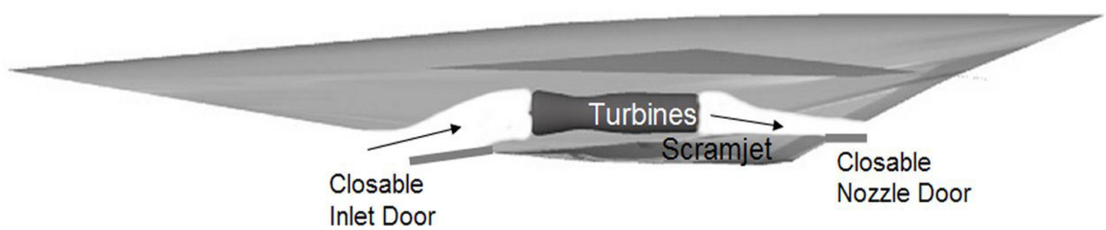


Figure 3.13 Turbine Integration in Hypersonic Vehicle

The packaging of several large turbines and their required inlet and nozzle flowpaths within the vehicle uses up a large amount of volume which requires further sizing up of the vehicle to house the displaced fuel volume.

3.6. *Configuration Internal Layout*

3.6.1. Rocket Vehicle Layout

The internal layout of the components within the fuselage of the rocket vehicle is straightforward and very similar to other existing rocket vehicles. The rocket orbiter layout is the same as the booster layout with the exception of the volume reserved for the payload situated between the propellant tanks of the orbiter (see Figure 3.14).

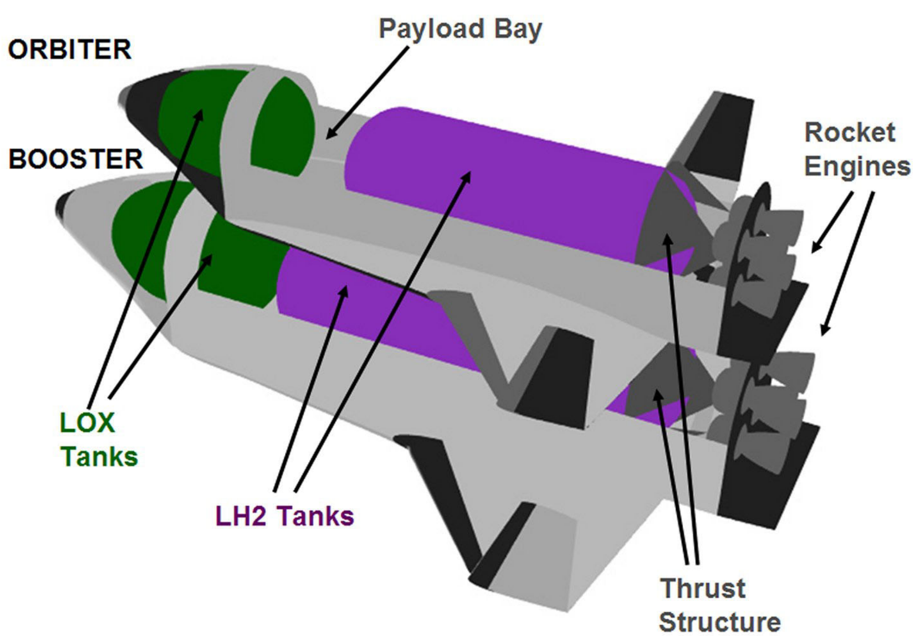


Figure 3.14 Internal Cutaway: TSTO All-Hydrogen Rocket

Noticeable in the cutaway view is the much larger hydrogen tanks versus the LOX tanks. The rocket engines are attached to a standard thrust structure. The wings are attached to the rear portion of the fuselage and are placed so that the wing box structure can pass beneath the hydrogen tank. The figure shows a TSTO all-rocket vehicle. The same orbiter and booster layouts were used for the TSTO air-breathing and rocket combined vehicles depending on whether a rocket orbiter or booster was used as part of the configuration.

3.6.2. Air-Breather Vehicle Layout

The internal layout of an air-breathing vehicle is much more complex than that of a rocket. This is due in part to the inclusion of additional components, including multiple separate propulsion systems. Additional constraints are added when it is considered that the air-breathing vehicle requires similar stability requirements as other high-speed aircraft. This analysis did not consider any stability, trim, or center of gravity issues in the vehicle solutions. A notional layout of an SSTO RBCC air-breather is shown in Figure 3.15.

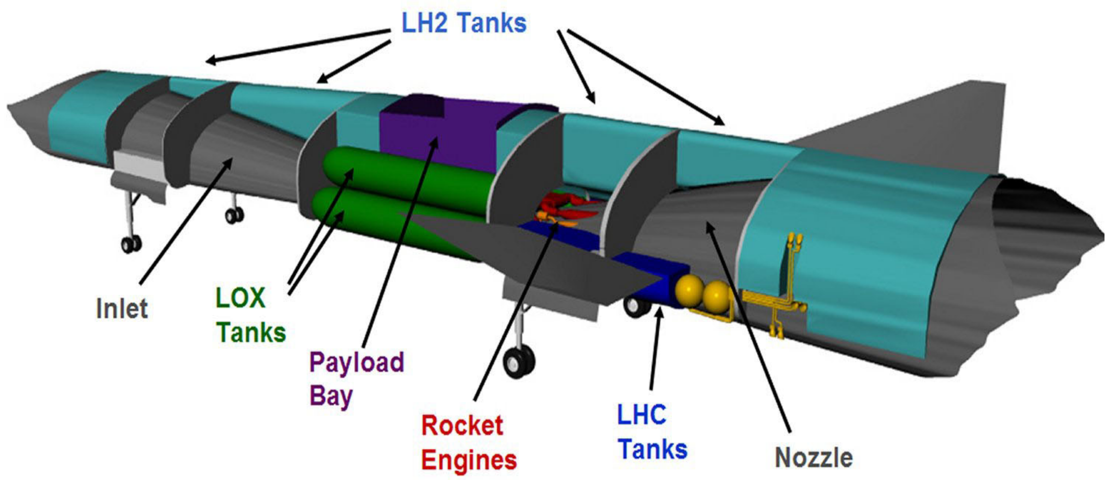


Figure 3.15 Internal Cutaway: SSTO Inward-Turning RBCC Air-Breather

The layout shown is for an inward-turning SSTO VTHL vehicle, but a nearly exact layout would be used for HTHL, 2D, or TSTO vehicles. In the figure, most of the port side LH2 tanks have been removed to reveal the inner components. The rockets are integrated in the scramjet nozzle as described in a previous section. The narrow height of the air-breather necessitates the location of the payload bay in the center of the vehicle; otherwise the envisioned 4.0 m diameter payload that was envisioned would stick out into the inlet or nozzle. This arrangement places the payload bay above the scramjet combustor which actually may prove beneficial for maintenance as access to the top of the combustor could be achieved through the payload bay floor without removing the combustor. The LOX tanks are cylindrical and are located near the midpoint of the vehicle. The LOX propellant composes nearly half of the gross weight so it is prudent to locate it near the supposed center of mass. The inward-turning geometry actually is quite beneficial for the integration of the landing gear as there are bottom surfaces of the vehicle which are not part of the propulsion flowpath. This allows for the placement of landing gear that does not suffer from the extension and sealing problems of gear that must deploy through the inlet or nozzle surfaces. The layout is shown for a vertically-launched air-breather; the landing gear for a horizontally-launched vehicle would be larger. This particular configuration used hydrocarbon fuel for its first trajectory segment rocket takeoff. As seen in the figure, the LHC tanks are quite compact due to the high packing density of the LHC fuel. In the layout shown, the LHC tanks are tucked on two sides of the rear landing gear wheel well. This is a cramped and angular area where it would be impractical to place conformal LH2 tanks. Being able to make use of otherwise unusable space by placing the LHC tanks here saves more usable volume for the conformal tanks. Finally, as shown in the figure, the majority of the vehicle volume is taken up by the conformal LH2 tanks. The vehicle is quite literally a flying hydrogen tank.

Chapter 4. TSTO Rocket: Baseline Vehicle

While the air-breathers represent a desired future capability, an all-rocket solution might constitute a satisfactory level of performance that is nearer-term and would require less technology development while accomplishing the same mission. The rocket results were therefore considered the benchmark against which to judge the extent of the improvement promised by the air-breathing configurations studied in subsequent chapters. The baseline configuration geometry is shown in Figure 4.1.

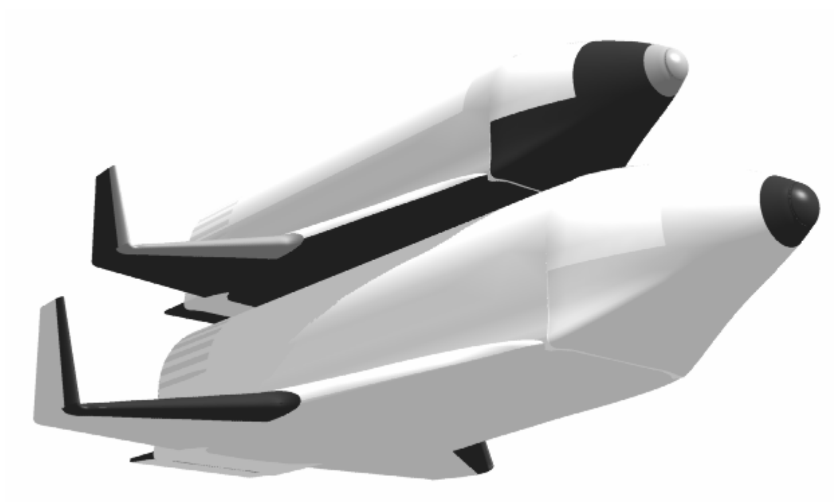


Figure 4.1 TSTO Rocket: Baseline Configuration

4.1. *TSTO Rocket Vehicle Setup*

The TSTO rocket configuration was the starting point for a trade study considering different fuel types. Three TSTO rocket variations were created and sized for this study. The three configurations include: hydrogen fuel in booster and orbiter (HR/HR), all hydrocarbon fuel (HCR/HCR) and a combined rocket (HCR/HR). The TSTO rockets are divided into two trajectory segments; one for the booster stage and one for the orbiter. The major configuration parameters are listed below:

- LH2 rockets use rubberized SSME engines with rocket installed thrust / weight of 73.5.
- LHC rockets use rubberized RD-180 engines with rocket installed thrust / weight of 80.
- Booster rocket engines sized for thrust to weight at takeoff of 1.4.
- Orbiter rocket engines sized for thrust to weight of 1.0.
- Rocket orbiter staging at 7000 ft/s.
- Orbiter ascent to 50 nm X 100 nm transfer ellipse after staging; OMS engines circularize 100 nm LEO orbit.
- TPS for rockets use Shuttle type materials, maximum temperatures and unit weights.
- TPS design point for the rocket booster is the staging velocity.

- TPS design point for reusable rocket orbiters is for re-entry conditions.
- Orbiter wings sized for landing based on empty weight + payload weight and landing velocity of 180 knots.
- Orbiter landing gear sized for landing: 4.8% of empty weight + payload weight (provides for abort scenario if accompanied by fuel dump).
- Booster wings sized for landing booster empty weight and landing velocity of 180 knots.
- Booster landing gear sized for landing 4.8% of booster empty weight
- All booster stages are recovered with a turbojet fly-back system and returned to the launch site.

4.2. TSTO Rocket Vehicle Results

4.2.1. Gross Takeoff Weight and Scale Comparison

The three vehicles were created and solved within the design code for the reference mission of 20,000 lb to LEO. The gross takeoff weights and lengths of the three sized TSTO rockets are shown in Figure 4.2.

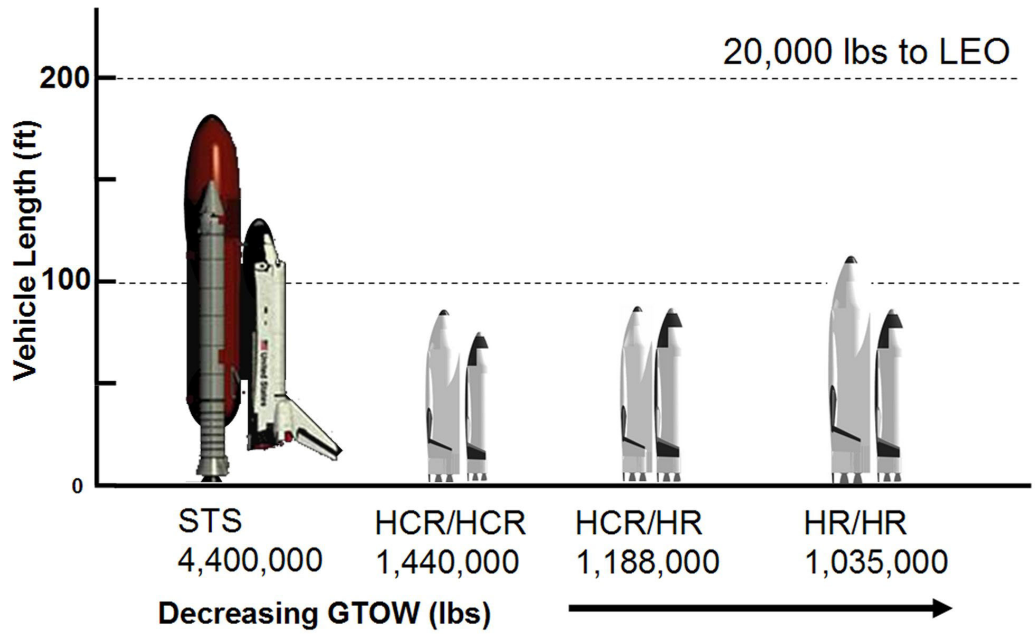


Figure 4.2 TSTO Rockets: GTOW and Scale Comparison

The Space Shuttle is included for scale reference and should not be used for direct comparison as it is sized for carrying approximately 60,000 lb to LEO. As would be expected, the higher Isp of the pure hydrogen HR/HR rocket results in a smaller fuel requirement to meet the objective and therefore comes in at the lightest gross weight. The pure hydrocarbon rocket comes in at the heaviest. Though the lightest, the all-hydrogen HR/HR rocket is the largest vehicle of the three because of the low density fuel while the heaviest vehicle, the HCR/HCR is the smallest geometrically. An interesting rocket is the HR orbiter atop an HCR booster. The HR orbiter is the same size as the other HR orbiter from the HR/HR case, as they fly the same trajectory from the same starting point and initial velocity. However, since the HR orbiter has a smaller gross weight than the HCR orbiter from the HCR/HCR case, its HCR booster can be sized down slightly thus reducing the total gross weight somewhere between the values of the all-hydrogen and all-hydrocarbon cases.

4.2.2. Gross Weight Breakdown and Comparison

The same sizing trend witnessed above is also seen in Figure 4.3 where the gross weight is broken down by propellant segments and vehicle stage empty weight.

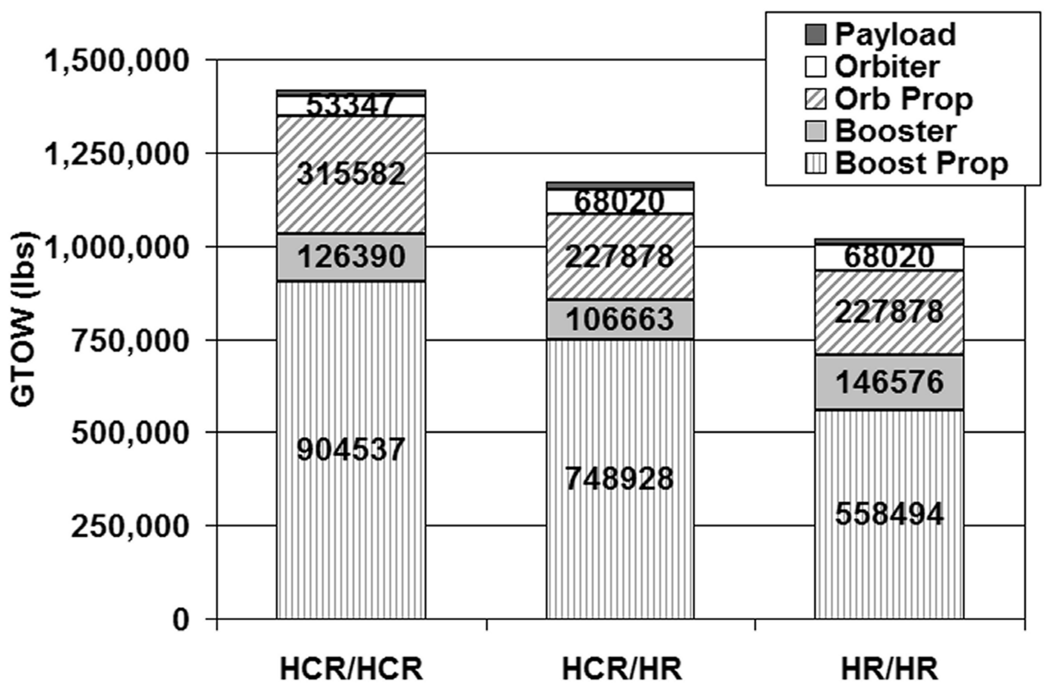


Figure 4.3 TSTO Rockets: Gross Weight Breakdown

The two HR orbiters are confirmed in this figure to be precisely the same with the differences in the boosters caused by different booster propellant selections. The two HCR boosters are also shown which, though sharing the same propellant choice, size differently due to the difference in the gross weights of their respective orbiters.

4.2.3. Empty Weight Comparison

The unforeseen outcome of the combined HCR/HR rocket was its resulting empty weight. While the combo was the medium performer in total gross weight with a heavier gross weight HCR booster than the HR booster, the higher packing density of the hydrocarbon fuel in that HCR booster makes for a geometrically smaller booster than the hydrogen case. The total empty weights of the three vehicles are shown in Figure 4.4.

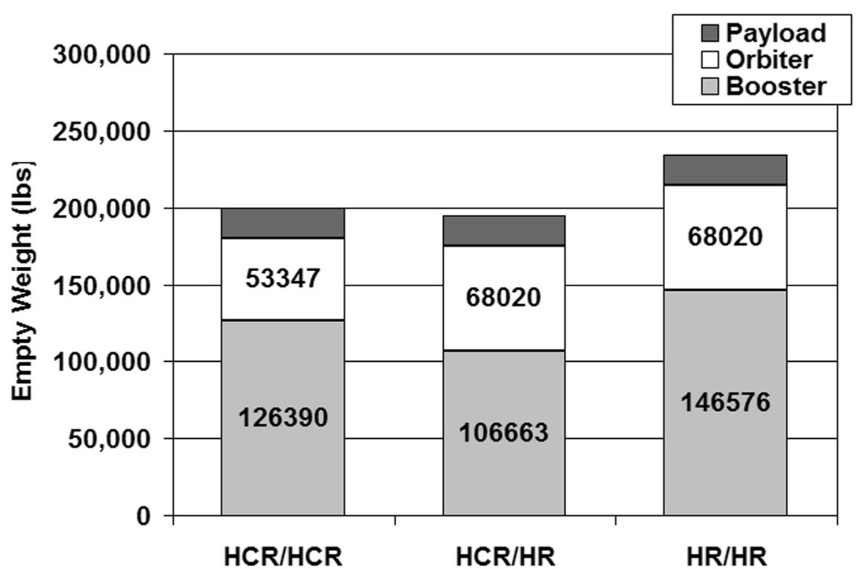


Figure 4.4 TSTO Rockets: Empty Weight Comparison

This is an example where using a fuel with a lower Isp but a higher density might decrease the rocket empty weight and consequently the cost of the vehicle. This causes the stages using hydrocarbon to have reduced empty weights versus hydrogen fueled stages.

It is interesting to observe the change in vehicle weight throughout the entire trajectory to witness the trends noted above. Figure 4.5 shows the values of total vehicle weight for the all-hydrogen and all-hydrocarbon TSTO rockets as a function of the ascent velocity.

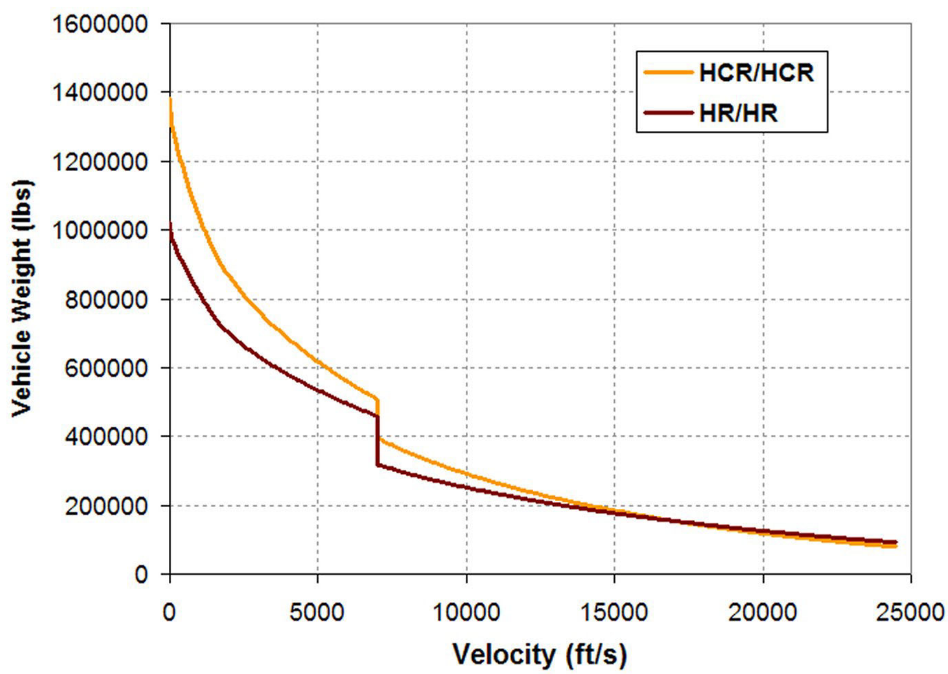


Figure 4.5 TSTO LHC and LH2 Rockets: Vehicle Weight across Ascent Trajectory

As seen in the figure, the HCR/HCR rocket starts with the higher gross weight, but the difference between its weight and that of the HR/HR rocket decreases as the booster fuel is expended. At staging, the now empty booster is discarded causing an immediate drop in total vehicle weight proportional to the loss in booster empty weight; the drop is larger for the HR/HR configuration because its booster has a larger empty weight. As the orbiters continue their ascent the total weight of the HCR orbiter actually drops below that of the HR orbiter at about 18,000 ft/sec. The weights at the far right of the figure correspond to the orbiter empty weights.

4.2.4. Orbiter Empty Weight Breakdown and Comparison

The empty weight breakdown by component for the rocket orbiter plus the booster is found in Table 4.1.

Table 4.1 TSTO Rockets: Orbiter Empty Weight Breakdown

VEHICLE	HCR/HCR	HCR/HR	HR/HR
Propulsion	9241	9627	9627
Tank Stack	4298	7725	7725
Passive TPS	3384	4888	4888
Wing Total	11714	13751	13751
Landing Gear	3476	4072	4072
Other Rocket	21235	27957	27957
Orbiter Empty Wt.	53347	68020	68020
Booster Empty Wt.	126390	106663	146576
Total Empty Wt.	**179737**	**174683**	**214596**

Even though the fuel requirement of the HCR orbiter is larger than the HR orbiter, the fuel fits into a smaller, less complex tank. This tank volume reduction decreases the total surface area of the rocket and hence lowers the TPS weight. This weight savings coupled with the weight reduction in the tank weight allows the scaling down of the orbiter wing and landing gear making the HCR orbiter the lightest empty weight of the orbiters. It must be remembered however that the HCR booster was sized to carry the HCR orbiter's gross weight. Therefore, the HCR booster required for the HCR orbiter is larger and heavier than the HCR booster required for the lighter weight HR booster. These results indicate that the greatest reduction in empty weight is achieved for gross weight reductions in the orbiter, and for vehicle size (empty weight) reductions in the booster. In this particular sizing, the slight empty weight reduction of the HCR/HR rocket over the HCR/HCR rocket may not be as beneficial as having a non-cryogenic fueled HCR orbiter, so again, operations issues help to define the "best" answer.

4.3. TSTO Rocket Configuration Conclusions

From the results of the work performed during this investigation, the following conclusions may be drawn:

<u>TSTO Rocket Conclusions</u>

- HCR/HCR is the largest GTOW but smaller size choice (empty weight)
- HR/HR is the smallest GTOW but largest size choice (empty weight)
- Using LHC in the First Stage and LH2 for Second stage, HCR/HR yields the lightest Empty Weight (both stages together) of the three cases considered, even slightly less than the HCR/HCR case.

However, the operational ease of using the same, non-cryogenic fuel in both stages is an operational advantage that, for the slight empty weight increase, likely makes the pure hydrocarbon HCR/HCR rocket the best TSTO rocket choice for further attention.

Chapter 5. SSTO Air-Breathing Vehicles

There has been great interest in the development of single-stage-to-orbit vehicle systems during the past two decades. There have been many attempts at SSTO rocket configurations attempted without any significant progress towards the achievement of a practical launch vehicle. Air-breathing technology may provide the additional performance boost required to make an SSTO vehicle a reality. It is envisioned that SSTO vehicles would have reduced operations cost and turn-times versus TSTO vehicles. The TSTO rocket was established in the previous chapter as the configuration to beat. This chapter considers both inward-turning and 2D inlet geometry air-breathers. Configuration trades are performed on propellant selection and takeoff mode.

5.1. SSTO Air-Breathing Vehicle Setup

Chapter 3 included numerous figures containing representations of SSTO geometries. A total of nine SSTO vehicle systems were created. There were four RBCC vehicles created for each of the inlet geometries; two HTHL and two VTHL differing by propellant selection. The ninth vehicle was an

HTHL 2D vehicle with TBCC propulsion for the first trajectory segment. Listed below are the major configuration parameters used in setting up the SSTO air-breathers which apply to all considered vehicle systems. The three sections following that describe more particular setup parameters of the three vehicle propulsion and propellant categories.

- Rockets embedded in the scramjet nozzle were used for both low-speed and orbital insertion for SSTO. One SSTO vehicle case was solved with turbojets replacing the rockets for Trajectory Segment #1.
- LH2 or LHC rocket or turbine for Trajectory Segment #1: takeoff to ramjet start at 2,500 ft/s.
- LH2 Ramjet/Scramjet for Trajectory Segment #2; scramjet cutoff when computed EISP falls below approximately 700 seconds (~15,500 ft/s for inward-turning inlets, ~14,000 ft/s for 2D RBCC, and 13,000 ft/s for 2D TBCC.)
- Trajectory Segment #2 is the air-breathing part of the trajectory and is flown at a constant dynamic pressure of Q = 2000 psf.
- LH2 Rocket ascent to 50nm X 100 nm transfer ellipse after Scramjet end; Trajectory #3. OMS engines circularize 100nm LEO orbit
- Vehicles make use of variable geometry in the engine cowl region for ramjet starting and for improved off-design performance.

- TPS for air-breathers use more advanced TABI/FRICI materials.
- Thermal Protection System (TPS) matched for conditions at scramjet design point.

5.1.1. SSTO HTHL RBCC Air-Breather

For horizontal takeoff configurations of either inlet type or propellant selection, the following inputs were applied:

- Rocket engines sized for Thrust / Weight at takeoff of 0.7; provides for good transonic capability.
- Landing Gears sized for takeoff: 2.97% of GTOW.
- Wings sized for takeoff based on GTOW.
- Takeoff speed = 225 knots.

5.1.2. SSTO VTHL RBCC Air-Breather

The following inputs were used for vertical takeoff vehicles of either inlet geometry or propellant selection:

- Rocket engines sized for Thrust / Weight at takeoff of 1.4.
- Landing Gears sized for landing: 4.8% of Empty Weight + Payload Weight (provides for abort scenario if accompanied by fuel dump).
- Wings sized for landing based on Empty Weight + Payload Weight.

- Landing speed = 180 knots.

5.1.3. SSTO HTHL TBCC Air-Breather

The final configuration of this study involved an SSTO HTHL 2D vehicle in which the low-speed propulsion system is changed from rockets to after-burning turbojets. The TBCC vehicle would still require a rocket system for the final ascent to orbit, but the higher thrust required for takeoff and initial ascent would be provided by the much higher-Isp turbine engines. As discussed in Chapter 3, the integration of the turbines into the hypersonic vehicle is a geometry challenge. The turbine engines must be placed where there is sufficient volume to contain them, and allowance must be made to provide them with the requisite mass capture. This study assumed an "over-under" configuration[26] where the turbines are arranged in a parallel row located directly above the scramjet combustors. Closable inlet and nozzle doors are opened to permit mass flow. Such arrangements are more easily accommodated by the 2D vehicle geometry. The convergence of the inward turning inlet makes it challenging to efficiently package the turbines and was not attempted in this study. The six turbines themselves were sized using methods described by Raymer[27] for the resultant weight and dimensions of the engines based on the thrust required. A 20% reduction in the required weight and length were then made as suggested by Raymer[27] to account for recent advances in turbine engine technology. A multiplier of 1.4 was applied to the data for the uninstalled turbines to account for installation. When turbine engines were used for the first trajectory segment for the SSTO, they are sized with a thrust to weight requirement of 0.5. The lower value versus the 0.7 used for the rocket takeoff versions is a compromise between turbine size and transonic ability.

5.2. SSTO Vehicle Results (LH2 Fuel)

As with the previously presented rocket results, vehicle and component weight data are the primary means used in this study to report the results of the various vehicle cases. It is important to note that such data detail the design of the closed vehicle and are indicative of the vehicle's response to requirements, flight conditions, and vehicle performance parameters and may therefore be successfully employed to compare and contrast the different configurations and technologies. Four vehicles were setup and solved using liquid hydrogen as the fuel for the scramjet and takeoff and ascent rockets; two SSTO VTHL RBCC air-breathers (one with 2D inlet, the other inward turning), and two SSTO HTHL RBCC air-breathers (one with 2D inlet, the other inward turning). The results presented next.

5.2.1. Gross Takeoff Weight and Scale Comparison

The RBCC air-breathing configurations were closed as purely hydrogen fueled vehicles and were the first to be analyzed as part of the SSTO study. The sized vehicles with their corresponding gross takeoff weights (GTOW) are shown in Figure 5.1 arranged by decreasing GTOW (the STS is depicted for scale reference).

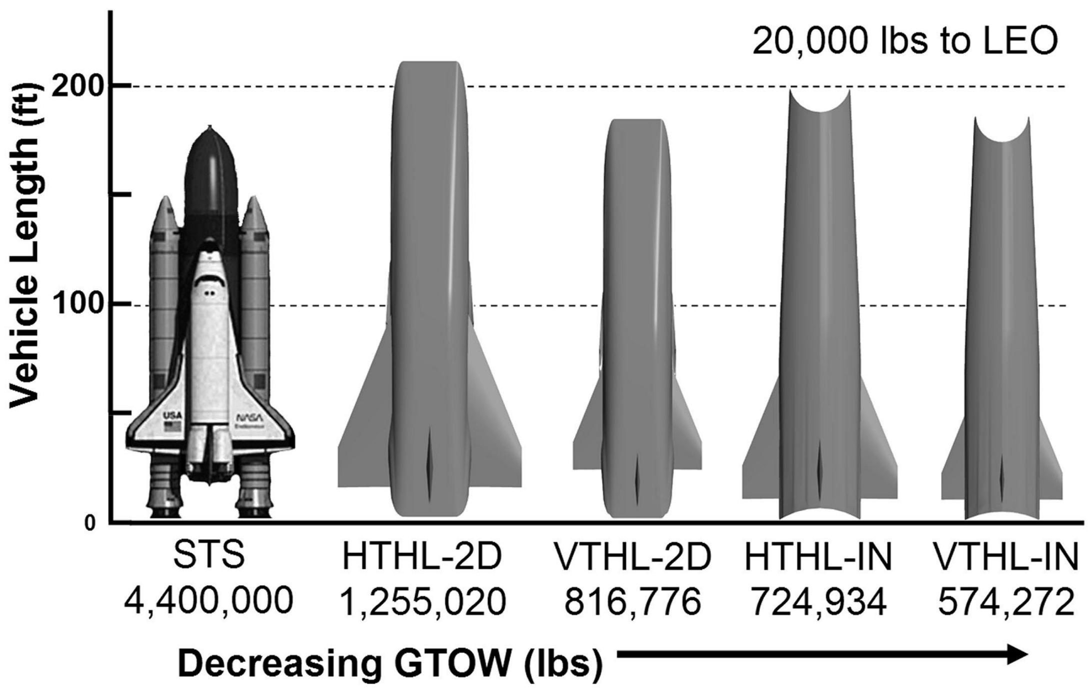


Figure 5.1 SSTO LH2 Air-Breathers: GTOW and Scale Comparison

The lightest GTOW was achieved by the vertically launched inward turning vehicle at about 600,000 pounds. The horizontal takeoff 2D inlet vehicle was over twice as heavy at 1.2 million pounds. Both HTHL vehicles are substantially heavier in GTOW than their VTHL counterparts due to the scaling up caused by the larger wing and landing gear weight. However, the inward-turning VTHL vehicle only grew by 26% to become HTHL while the 2D inlet VTHL vehicle had to grow 54% to close as an HTHL vehicle. The performance gap between the two inlet types grows larger as the scale increases. The decreased flowpath drag and cooling requirement of the inward-turning design over the 2D wedge inlet yield enough performance increase to allow the HTHL inward turning vehicle to come in at a lower GTOW than even the VTHL 2D vehicle. These results show the importance of analyzing hypersonic technology in context of the integrated system. A small difference in performance of the two scramjet inlets in a laboratory test is magnified when the vehicle using the lower performance inlet must be sized and resized for the increased cooling requirement and iteratively scaled up to closure.

5.2.2. Gross Weight Breakdown and Comparison

Depicted in Figure 5.2 is the GTOW of the four SSTO hydrogen vehicles broken down by payload weight, vehicle weight (empty weight), and the propellant weight required for each segment of the ascent trajectory.

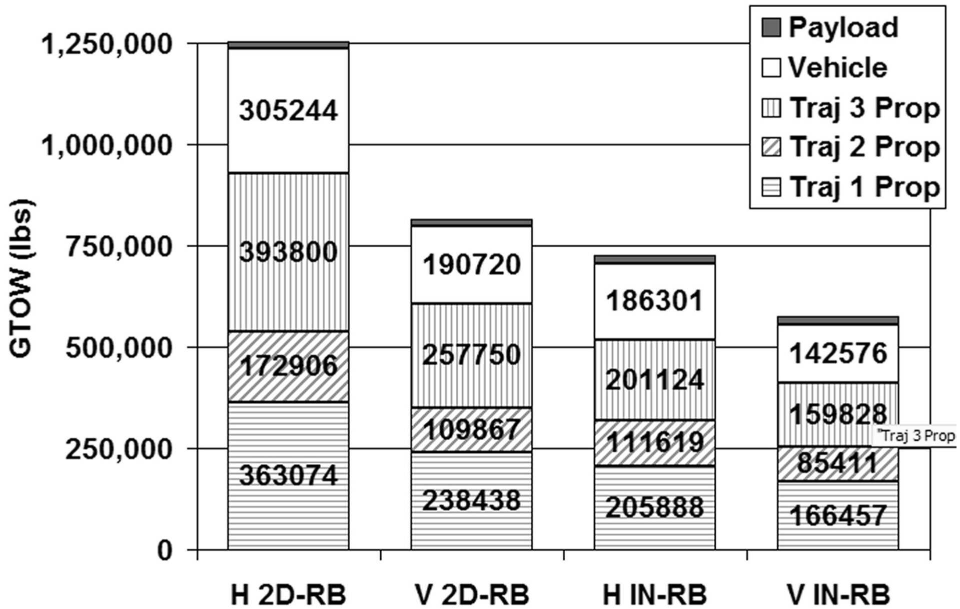


Figure 5.2 SSTO LH2 Air-Breathers: Gross Weight Breakdown

The propellant weight of the first and third trajectory segments are the combined weight of the hydrogen and liquid oxygen required for the rockets with hydrogen to oxygen weight ratio of 1:6. Trajectory segment #2 is the air-breathing part of the ascent and the propellant weight is of the hydrogen fuel only. The data show that almost 30% of the GTOW is expended in the first few minutes of the trajectory by the rocket engines accelerating the vehicle towards Mach 2.5 and ramjet/scramjet start. This is of particular interest because once the fuel is expended it no longer weighs the vehicle down, but the tank weight and vehicle size initially required to contain that expended propellant are part of the vehicle empty weight and must be carried throughout the mission.

It is interesting to note from Figure 5.2 that the hydrogen fuel used during the air-breathing trajectory segment#2 is much less than the propellant weight required for the rocket trajectory segments #1 and #3. But, since the rocket propellant weights include the weight of the oxidizer, the actual hydrogen propellant weight for segments #1 and #3 is one-sixth of the represented value. Added up, this means that approximately 60% of the on-board hydrogen is for the air-breathing trajectory. Though it does not add largely to the vehicle gross weight, the need to carry this hydrogen is the principal contributor to vehicle volume for these SSTO configurations.

5.2.3. Empty Weight Breakdown and Comparison

The empty weights are represented in the previous figure as the vehicle weight, and they follow the same trend as the gross weights. However, the HTHL IN inward-turning vehicle, which is approximately 90,000 lb lighter than the 2D VTHL in gross weight, is only 4400 lb lighter in empty weight due to its heavier horizontal structural components. As discussed in Chapter 2, most of the initial design and procurement costs of a launch vehicle scale with empty weight. Further understanding is gained by looking at the empty weight breakdown by components as shown in Table 5.1.

Table 5.1 SSTO LH2 Air-Breathers: Empty Weight Breakdown

Vehicle Type	H 2D-RB	V 2D-RB	H IN-RB	V IN-RB
Propulsion	59752	47864	36187	34937
Tank Stack	65514	42520	39103	30708
Active TPS	33995	26880	17485	15472
Passive TPS	35273	27226	31885	27677
Wing Total	30653	9639	14013	6107
Landing Gear	37275	9618	21531	7384
Misc. Vehicle	42783	26973	26097	20291
Empty Weight	**305244**	**190720**	**186301**	**142576**

This kind of breakdown gives quick insight into the requirements of the different configurations. The tank weights and surface areas scale up as the propellant volume increases. An increase in surface area increases the amount of area needing active and passive thermal protection. The two HTHL vehicles are readily identifiable in Table 1 by their large landing gear weights. The value for wing totals include the wing structure and wing TPS weight and are again conspicuous for HTHL. The values for the actively-cooled TPS directly demonstrate the larger cooling requirement of the 2D inlet compared to the inward turning; almost twice the amount comparing VTHL 2D to VTHL IN or HTHL 2D to HTHL IN. A remarkable observation is that the weights of the propulsion systems are roughly the same across the different vehicles. The reason for this is the way the ascent rockets are sized. The VTHL vehicles, while lighter than their HTHL counterparts, have rockets that are sized for thrust to weight equal to 1.4 where the HTHL rockets are sized at 0.7. The result is that the rocket propulsion makes up a greater percentage of the VTHL empty weight, which nearly matches the lower percentage rockets of the larger HTHL vehicles.

5.3. SSTO Vehicle Results (LHC 1st Trajectory)

The impact of using hydrocarbon fuel for the ascent rockets of the RBCC air-breathers was next considered. From the results of the TSTO rockets it was learned that using hydrocarbon fuel in the last trajectory segment would increase the gross weight carried until that point and increase the sizing of the first and second trajectory segment components. However, reductions in vehicle empty weight could be possible by using the higher density fuel in the first trajectory segment.

5.3.1. Vehicle Gross Takeoff Weight and Scale Comparison

The final part of the study changed the fuel usage for the first trajectory segment rockets in the four SSTO air-breathers to hydrocarbon, with hydrogen use remaining during the ram/scram in trajectory #2 and for the final rocket ascent of trajectory #3. It should be noted that the rocket engines would not function on both hydrocarbon fuel and then hydrogen fuel, therefore, the weights of two different rocket engine sets must be accounted for in this analysis; an HCR engine set for trajectory segment #1 and an HR engine set for trajectory segment #3. The four air-breathing vehicles were resized and the closed vehicles are depicted according to decreasing gross weight in Figure 5.3.

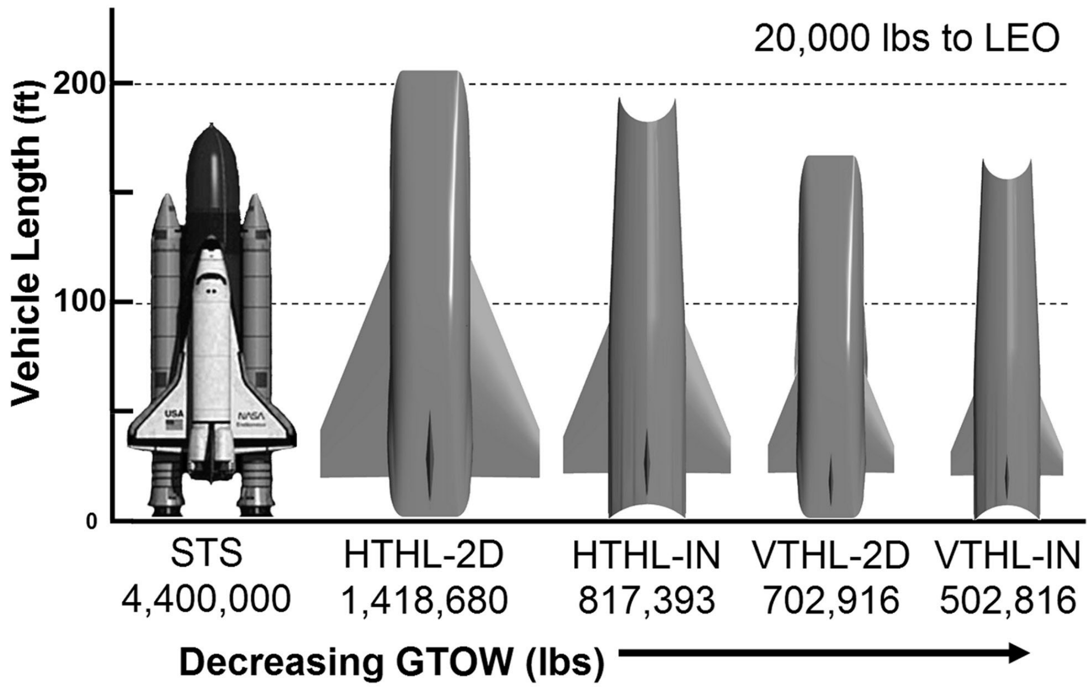


Figure 5.3 SSTO LHC 1st Air-Breathers: GTOW and Scale Comparison

The first change to note is that the gross weight of the HTHL IN is now greater than the VTHL 2D. The GTOW values have increased for the HTHL vehicles as was expected. The HTHL 2D grew by a 164,000 lb and the HTHL IN by 92,000 lb. The real surprise is that the GTOW values for the two VTHL vehicles have decreased substantially. The VTHL IN decreased by 72,000 lb and the VTHL 2D decreased by 114,000 lb when compared to their all hydrogen equivalents.

5.3.2. Gross Weight Breakdown and Comparison

A decrease in empty weight was expected as a result of the first segment propellant change, but a decrease in gross weight of the magnitude shown in the previous section was not anticipated. Further information on these results is provided by the gross weight breakdown shown in Figure 5.4.

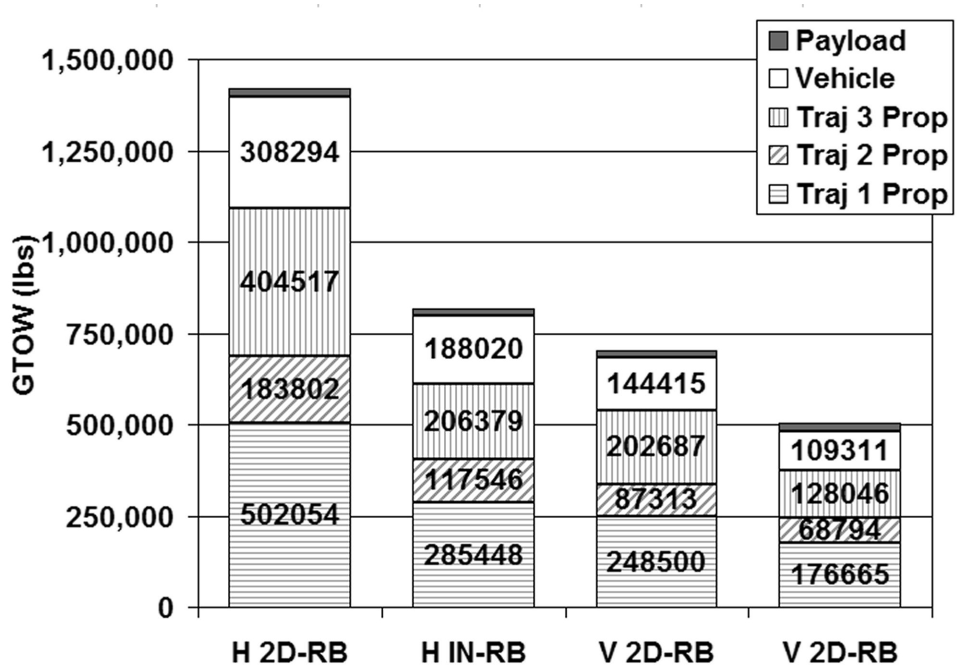


Figure 5.4 SSTO LHC 1st Air-Breathers: Gross Weight Breakdown

As should be the case, the hydrocarbon/LOX propellant weight required for the first trajectory segment is greater for all vehicles than the corresponding hydrogen/LOX required in the first set of LH2 air-breathing vehicles.

However, the hydrogen propellant weight required for the air-breathing second trajectory segment has decreased for the two VTHL vehicles. This indicates that the air-breathing segment is now being done more efficiently than previously.

5.3.3. Drag Comparison across Ascent Trajectory

Both of the VTHL vehicles have benefited from an empty weight reduction of over 40,000 lb. The decrease in vehicle weight is made possible mostly by a reduction in vehicle size enabled by a higher first segment propellant density. A higher first segment density results in a vehicle that begins its air-breathing trajectory segment with less empty volume than a vehicle with a lower first segment propellant density. A smaller vehicle benefits from reduced surface area and consequently lighter TPS weights. The smaller vehicle also decreases the amount of drag that must be overcome; especially during the high-drag hypersonic air-breathing portion of the trajectory. The total drag for both propellant loadings of the VTHL 2D air-breather is shown in Figure 5.5.

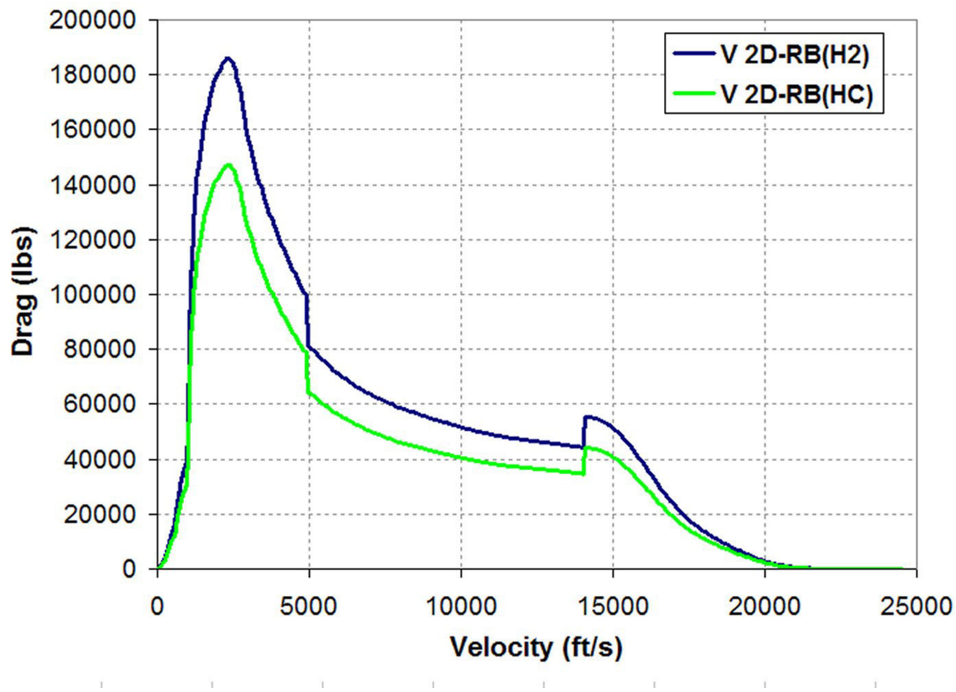


Figure 5.5 SSTO LHC 1st and LH2 Air-Breathers: Drag Comparison of VTHL 2D

The lower drag of the V 2D-RB(HC) enables a more efficient air-breathing segment. These results indicate an even stronger incentive for reducing air-breather vehicle empty weight (size) than was discovered for the TSTO rockets.

5.3.4. Empty Weight Breakdown and Comparison

The weight trends may be seen in the empty weight breakdown by component shown in Table 5.2.

Table 5.2 SSTO LHC 1st Air-Breathers: Empty Weight Breakdown

VEHICLE	H 2D-RB	H IN-RB	V 2D-RB	V INRB
Propulsion	61058	37300	36254	26814
Tank Stack	59998	35898	29089	21448
Active TPS	32114	16888	22078	12618
Passive TPS	33439	30545	21793	22278
Wing Total	37236	17137	7563	4882
Landing Gear	42135	24277	7547	5903
Misc Vehicle	42313	25975	20092	15368
Empty Weight	**308294**	**188020**	**144415**	**109311**

The impact of the reduced vehicle size imparts broad savings to the solution. Reductions in tank weight and active and passive TPS weights were achieved in each vehicle configuration. However, the increased GTOW of the horizontal takeoff vehicles immediately scales up their wing and landing gear weights. This increase effectively swallows up any gains made in packaging and consequently influences empty weight by very little while still increasing gross weight of the HTHL vehicles. The HTHL 2D vehicle would become the largest aircraft to have ever flown. Horizontal takeoff may still be possible; the HTHL inward-turning vehicle is still small enough to be realistically operated from traditional runways. However, the best performer of the eight SSTO configurations evaluated thus far is the half-million pound VTHL inward turning vehicle.

5.4. *SSTO TBCC Vehicle Results*

The final vehicle configuration analyzed was an SSTO HTHL 2D vehicle with turbine engines replacing the first trajectory segment rocket engines that have been used for the previous eight SSTO vehicles.

5.4.1. Gross Weight Breakdown and Comparison

Figure 5.6 shows the gross weight breakdown of the sized 2D HTHL TBCC vehicle compared to the 2D HTHL RBCC vehicle with LHC for the first trajectory segment.

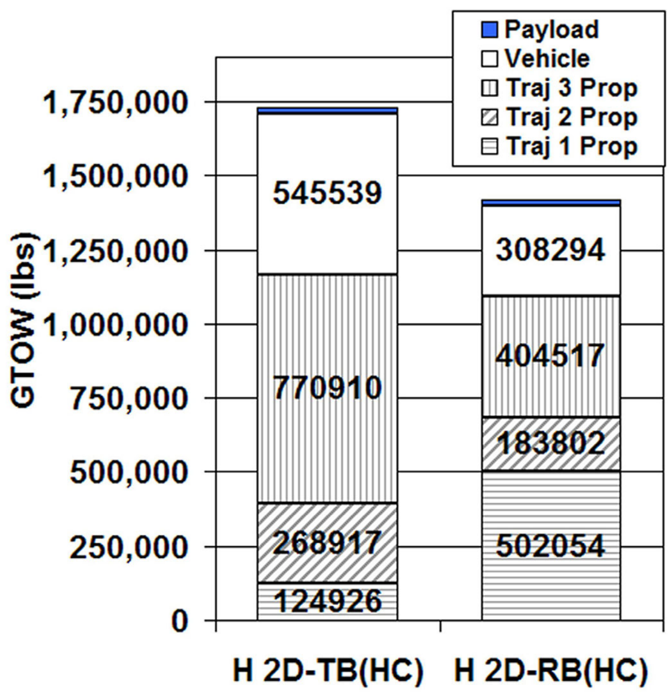


Figure 5.6 SSTO TBCC and RBCC Air-Breathers: Gross Weight Breakdown

These two configurations differ only by the choice of first segment propulsion, yet there are great differences in the resulting vehicle solutions. As expected, the use of the higher-Isp turbines has greatly reduced the propellant weight requirements for the first trajectory segment (and hence the propellant volume, though packaging of the dense hydrocarbon was never a problem). However, once the turbines have ceased operation, they are part of the vehicle empty weight and must be carried all the way to orbit. As seen in the figure, the empty weight of the TBCC vehicle is almost 240,000 lb heavier than the RBCC vehicle. This extra weight penalty requires the sizing up of the propulsion requirements for the second and third trajectory segments. At the end of the scramjet trajectory, the TBCC vehicle still weighs 1.3 million lb, nearly twice the 700,000 lb of the RBCC vehicle at the same point in the trajectory. This means that the thrust and propellant requirements of the third trajectory segment ascent rockets must be doubled.

5.4.2. Empty Weight Breakdown and Comparison

These impacts are clearly evident in Figure 5.7, which details the empty weight breakdown by components.

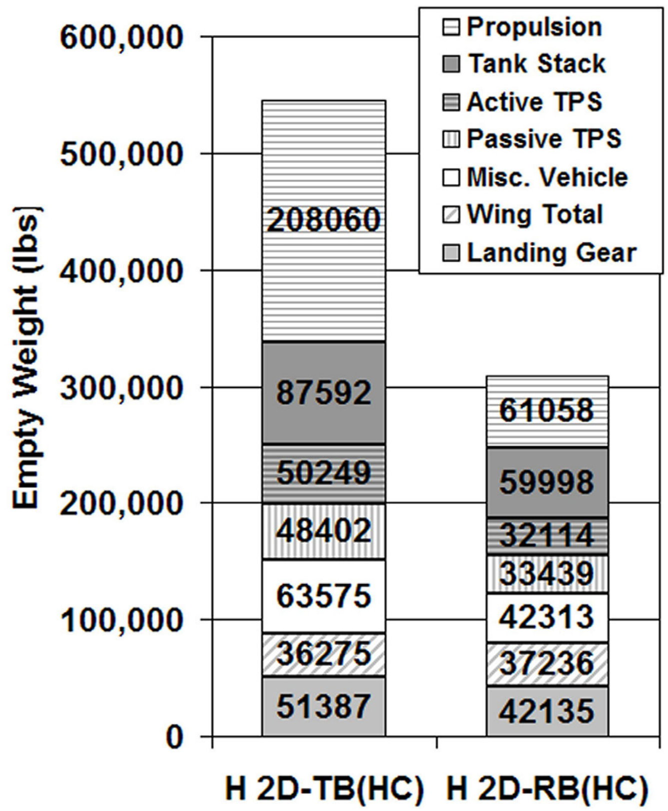


Figure 5.7 SSTO TBCC and RBCC Air-Breathers: Empty Weight Breakdown

The weights of the TBCC propulsion components are more than three times greater than for the RBCC. This increase is due to the over 100,000 lb of weight for the six turbojets, the doubling of the weight of the third segment rockets, and to the increased RCS and OMS requirements of a much larger on-orbit vehicle. Besides the weight penalty, the turbine engines also impact the volume of the vehicle. Each engine for this case is 9.5 ft in diameter and over 25 feet long. This is clearly beyond the experience base of current turbines, but then, so are 1.7 million pound aircraft. Combined with the volume removed for the inlet and nozzle passageways the turbines use up

21,500 ft^3 of volume; approximately 20% of the usable interior volume for this vehicle. Also, the fuselage width of this vehicle had to be stretched in order to accommodate the combined 57 ft width of the six engine diameters. When these impacts are considered together, the use of a turbine system is a very unattractive choice for an SSTO air-breather. In fact, the empty weight of the HTHL TBCC vehicle is more than the gross weight of the VTHL RBCC inward-turning vehicle with hydrocarbon 1st trajectory segment!

5.5. SSTO Air-Breather Comparison to TSTO Rockets

This section now compares the SSTO air-breathers of the current chapter with the TSTO rockets solved in the previous chapter. The results presented thus far demonstrate the necessity of performing analyses on completely integrated vehicles. The coupling of the propulsion, airframe, aerodynamics, gravity loss, volumes, heating loads, and weights all interact to determine the performance and penalties associated with a given vehicle configuration. This is especially true for the air-breathing SSTO configurations. In many cases the results presented verify the trends that would be expected for a given configuration, such as the heavier GTOW of the all-hydrocarbon rocket over the purely hydrogen one. The value added by this analysis is that these trends are now quantitative and therefore measurable and directly comparable to other configurations. Of even greater interest is the understanding gained from the results of an unanticipated or non-intuitive interaction, as was witnessed in the data of the LHC/LH2/LH2 air-breathers. The SSTO air-breathers and TSTO rockets are compared below in terms of several of the figures of merit.

5.5.1. Wetted Area Comparison

A valuable understanding seen in the previous solutions was the coupling between vehicle size, aerodynamic drag, and the amount of required TPS. Specifically, the skin friction drag and TPS both scale with the wetted area of the vehicle. For the heating conditions present during either the air-breathing trajectory or atmospheric re-entry, all the exposed area of a hypersonic vehicle will require some level of TPS. When the heating over a certain area exceeds the limits of current materials technology, then those areas must be actively cooled. The reduction of TPS area yields a double benefit, the first being a reduction in weight, and second a reduction in the time and cost of TPS refurbishment. The actively-cooled panels on future hypersonic vehicles are a new TPS system that is likely to require a fair amount of inspection and between flight refurbishment. Figure 5.8 compares the wetted areas of all twelve vehicles and also represents the amount of that area that must be actively cooled.

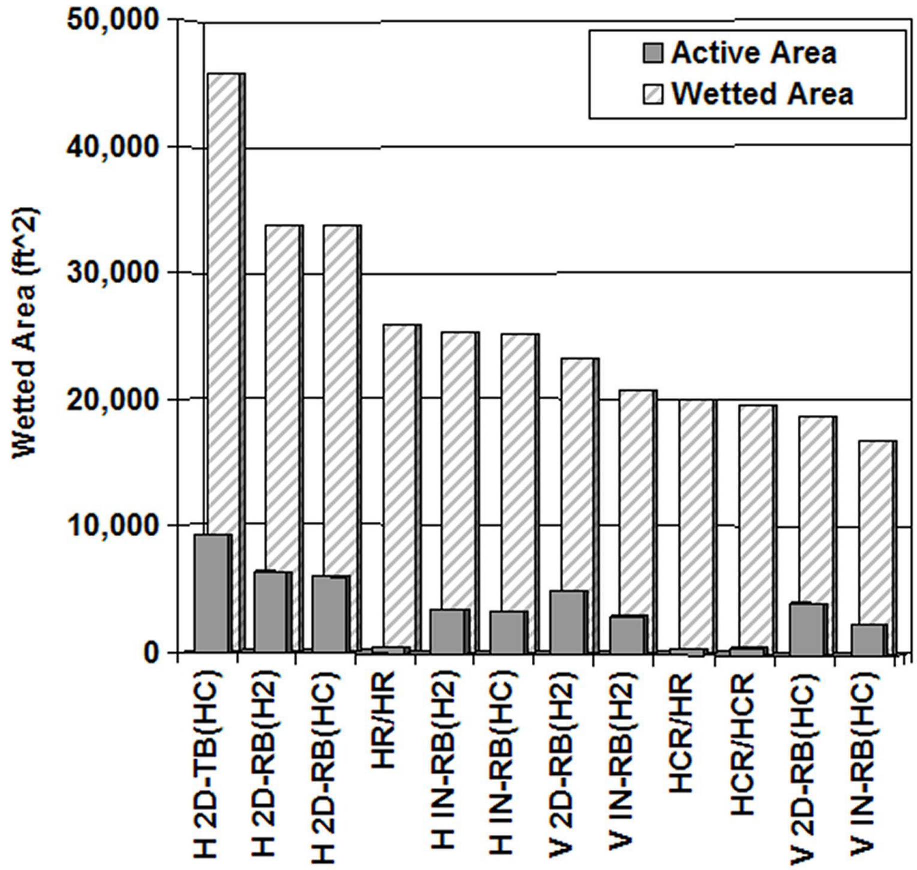


Figure 5.8 TSTO Rockets and SSTO Air-Breathers: Wetted Area Comparison

The wetted areas of the TSTO HCR rocket combinations come in lower than all but the hydrocarbon VTHL air-breathers. The pure hydrogen HR/HR rocket, though it has the lightest gross weight of the three rockets, has the largest wetted area of the three because of its increased size. The active cooling area for the rockets is minimal as it is only required in the combustion chambers and nozzles. The air-breathers; however, need substantial active cooling through the extreme parts of the inlet and nozzle and throughout the combustor. Also shown in the previous figure is the improvement in active cooling requirements of the inward turning over the 2D air-breathers. In terms of wetted area, the TBCC and RBCC HTHL 2D air-breathers are clearly the worst performers. However, the VTHL air-breathers are actually fairly competitive with the HCR rockets in total wetted area. The basic wetted area trends favor vertically-launched SSTO air-breathers, and TSTO rockets with hydrocarbon boosters.

5.5.2. Gross and Empty Weight Comparison

The total gross and empty weights of the twelve vehicles considered in this report are all compared in Figure 5.9 and are arranged by decreasing empty weight.

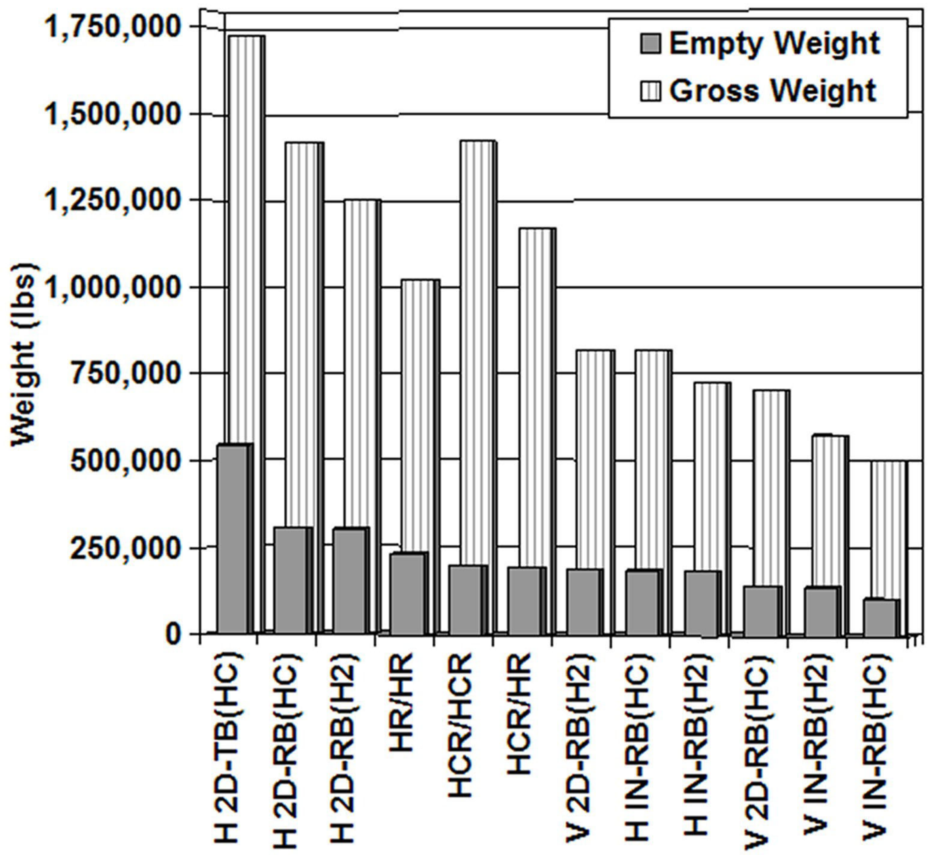


Figure 5.9 TSTO Rockets and SSTO Air-Breathers: Gross and Empty Weight Comparison

In terms of empty weight, the "best" air-breathing configurations for space-access with the given payload requirement are the VTHL inward-turning air-breathers. They also enjoy the lowest values of GTOW. In general the SSTO air-breathers (with the exception of the HTHL 2D vehicles) come in with lighter empty weights and reduced GTOW compared to the TSTO rockets. It is important to note however, that if the expected level of scramjet technology fails to completely mature, the baseline air-breathing vehicles presented here could all grow substantially and the TSTO rockets would look more favorable. The HTHL 2D baseline cases are probably already too large to be realistically managed as horizontally launched vehicles and any increase in size would completely invalidate them for operation from existing runways. The TBCC HTHL 2D is particularly unmanageable; with an empty weight larger than the gross weight of several of the VTHL vehicles to accomplish the same mission. Though the VTHL air-breathers come in at the lightest in both weight categories, the HTHL inward-turning all hydrogen air-breather still remains a possible choice should a horizontal vehicle be required.

Figure 5.10 shows the total weights of the best vehicles in each configuration category across the entire mission trajectory. The vehicles selected are the IN-RB(HC) and 2D-RB(HC) vehicles from the VTHL configuration, the IN-RB(H2) and 2D-RB(H2) vehicles from the HTHL configuration, the all hydrocarbon HCR/HCR rocket, and the 2D-TB(HC) SSTO turbine vehicle.

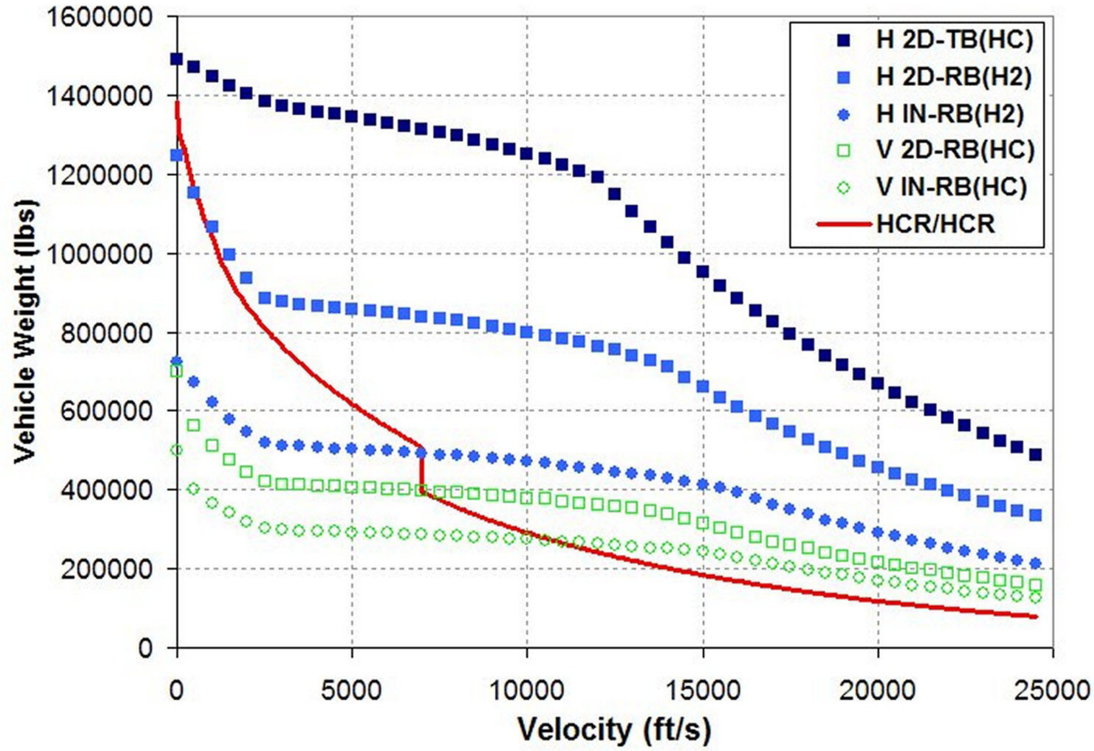


Figure 5.10 TSTO Rocket and SSTO Air-Breathers: Vehicle Weight across Trajectory

This figure provides tremendous insight into how the different vehicle configurations size across the flight trajectory. The high final weight of the TBCC vehicle on the right of the figure translates into a large amount of ascent rocket propellant, which sizes up all previous propulsion segments required to carry it. The four SSTO vehicles in the figure all have the same trend but are spread apart slightly by the final empty weight with the HTHL vehicles coming in heavier than the VTHL vehicles. The HCR/HCR rocket, though it starts with a high gross weight compared to the SSTO air-breathers, drops quickly into the same area as the VTHL air-breathers.

A horizontally operated and integrated, vertically launched VTHL benefits from both operational and performance gains and is consequently the most attractive configuration for SSTO air-breathers. For near-term launch capability, the fully reusable TSTO rockets are very comparable with the air-breathing vehicles in terms of empty weight and might be the next logical improvement over the partial reusability of current rocket launch systems. It must also be noted that, empty weight pound for pound, rockets are likely much cheaper to design and procure than air-breathing vehicles.

5.6. SSTO Configuration Conclusions

From the results of the work contained in this chapter, the following conclusions may be drawn:

5.6.1. Air-Breathing Inlet Conclusions

Inward turning inlets outperform conventional 2D wedge type inlets. The increased performance comes from a smaller heating load due to less surface area exposed in high heating regions. The reduced active cooling area requirement allows the vehicle to scale down thus reducing weights of everything from wings to landing gear as well as reducing the area requiring TPS.

5.6.2. SSTO VTHL Air-Breathers Conclusions

For VTHL SSTO options, using LHC in the low-speed rocket cycle (Trajectory segment #1) can yield great advantages:

- VTHL IN SSTO for this case is lightest vehicle overall in both GTOW and Empty Weights – even after accounting for two (LH2 and LHC) rockets carried simultaneously.
- The additional propellant weight due to LHC choice has no impact on wing and landing gear weights of a VTHL vehicle as it is expended before landing. This helps considerably in vehicle sizing.
- The more compact fuel storage of the hydrocarbon first trajectory segment yields a smaller vehicle which improves performance by reducing both vehicle weight and drag.
- The empty weight of this case is less than the best rocket TSTO case, the HCR-HR, and represents the development and acquisition of a single vehicle instead of both a rocket booster and rocket orbiter.

5.6.3. SSTO HTHL Air-Breather Conclusions

Conversely, for HTHL SSTO options, using an LHC rocket in the low-speed cycle yields no decrease in empty weight but penalizes the vehicle with an increase in GTOW. This outcome cripples the HTHL 2D vehicle but only moderately increases the HTHL IN. The all hydrogen HTHL IN is the best horizontal takeoff SSTO air-breather.

5.6.4. SSTO HTHL TBCC Air-Breather Conclusions

The TBCC HTHL 2D vehicle causes a chain reaction of negative impacts. The integration of the turbine engines uses up large amounts of volume and adds a large weight penalty all the way to orbit. These factors drive up the scaling of vehicle empty weight, surface area, upper trajectory propulsion requirements etc. For SSTO application, the TBCC system cannot compete with the use of RBCC for takeoff and for the low-speed trajectory segment.

5.6.5. General Air-Breather and Rocket Conclusions

The understanding gained from the fuel selection trade study suggest that as a general guideline it is better to reduce the gross weight of the vehicle during later trajectory segments and to reduce the empty weight (vehicle size) for the earlier points in the trajectory. The reasoning for this is sound; carrying weight over a longer portion of the trajectory, be it propellant weight or otherwise, requires a greater energy input per pound. Propellant weight used in the first trajectory segment is quickly expended and not carried for long, but the structure size and weight required to contain it are carried along. This is why more efficient propellant packaging may be better, even if the first trajectory segment gross weight is heavier (provided that the propellant still yields sufficient performance). This is even more applicable in the case of an air-breathing vehicle where a smaller vehicle not only means a reduction in the empty weight that is carried to orbit, but also of the drag during the air-breathing trajectory segment.

5.6.6. SSTO Air-Breather vs. TSTO Rocket Conclusions

As seen in the results of this chapter, a fully reusable TSTO hydrocarbon fueled rocket is tough to beat. In terms of the metrics of empty weight, wetted area, and technology readiness, and with the incorporation of recent operational practices and infrastructure, this configuration promises excellent capability for a near-term launch vehicle. The suite of future air-breathing vehicles offers solutions which can vary widely in scale and feasibility. Several of the VTHL vehicles are competitive with the TSTO rockets in terms of the figures of merit utilized and would offer the operational benefits of a single-stage launch vehicle. The use of hydrocarbon fuel during the first rocket segment of the VTHL inward-turning vehicle yields the most promising configuration of all those studied. The only HTHL vehicle that remains competitive is the all hydrogen inward-turning configuration.

Chapter 6. TSTO Combined Air-Breathing and Rocket Vehicles

Many proposed air-breathing launch vehicles are designed as two-stage configurations. The use of multiple vehicle stages is a means to reduce the amount of weight delivered to orbit by discarding expended stages. Indeed, multiple-stage configurations have been the only successful rocket-powered launch vehicles to date. From the viewpoint of an integrated launch system; the use of staging mitigates the vehicle scaling response that would otherwise be required for the successful design closure of a single-stage vehicle thus resulting in much smaller system weights and decreased design risk and uncertainty. These advantages are very attractive when a large amount of uncertainty exists in a proposed technology as is the case with hypersonic air-breathing propulsion. For these reasons, many industry and international designers have repeatedly investigated different staging configurations for air-breathing launchers. The present investigation seeks to compare these configurations and identify which merit further attention and developmental focus. An interesting question to be answered is whether these TSTO air-breathing configurations can compete with TSTO all-rocket vehicles, or if they are merely a stepping stone to achieve SSTO.

6.1. TSTO Configurations and Vehicle Setup

Wherever possible all vehicles were solved for the same set of input values except when the particular configuration category had a unique requirement, such as a thrust to weight ratio greater than one for a VTHL vehicle. In those cases, all of the vehicles within that category were run with the same assumptions. The payload requirement for each TSTO air-breathing and rocket combined configuration was the same as for the SSTO air-breathers and TSTO rockets of the previous chapters: 20,000 lb launched Easterly from Kennedy Space Center to the reference orbit. The general configuration parameters applicable to all vehicles are listed below with a description of each of the three configuration categories following.

- ♦ LH2 rockets use rubberized SSME engines with rocket installed thrust / weight of 73.5
- ♦ LHC rockets use rubberized RD-180 engines with rocket installed thrust / weight of 80
- ♦ Turbines use afterburning turbojets with (uninstalled, installed) thrust/weight ratios of (11, 8)

- TPS for rockets use shuttle type materials, maximum temperatures, and unit weights.
- TPS for air-breathers use more advanced TABI/FRICI materials.
- Air-breathing vehicles make use of variable geometry in the engine cowl region for ramjet starting and for improved off-design performance
- Hypersonic stages fly an air-breathing trajectory flown at a constant dynamic pressure of Q = 2000 psf
- Orbiter Wings sized for landing based on Empty Weight + Payload Weight and landing velocity of 180 knots
- Orbiter (Rocket or Air-Breather) Landing Gear sized for landing :4.8% of Empty Weight + Payload Weight (provides for abort scenario if accompanied by fuel dump)

6.1.1. TSTO HTHL Air-Breathing Booster with Rocket Orbiter

This configuration, show in Figure 6.1, is the most commonly proposed TSTO air-breathing launch vehicle and is comprised of a hypersonic ramjet/scramjet[5] first stage with an upper stage rocket[6] orbiter attached riding piggyback.

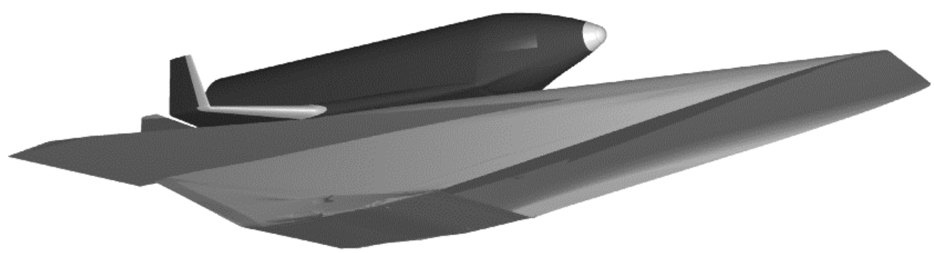


Figure 6.1 TSTO HTHL Air-Breathing Booster / Reusable Rocket Orbiter

The vehicle is horizontally processed and assembled and also takes off horizontally. Low-speed propulsion from takeoff until ramjet start is provided by either integrated turbine or rocket engines. The combined vehicle accelerates under ramjet/scramjet power until staging at some upper Mach number. The rocket orbiter is then ignited and ascends to orbit under its own power. After staging, the first stage decelerates and reverses course to fly back to the launch site which is now likely more than 1000 nm distant. The rocket orbiter in this configuration is exposed to the same heating envirnoment as the air-breather which is nearly analagous to the heating envirnoment the orbiter will experience during re-entry. However, much of the orbiter's leeward surface area which is shielded by the orbiter's attitude during re-entry, is here directly exposed to the high temperature flow and must be protected with additional, more capable TPS. Three versions of this configuration were solved as part of this study differing only by selection of low-speed propulsion cycle. One version utilized turbines[7]; the other two versions made use of either hydrogen or hydrocarbon rockets for takeoff and accelerations. The following configuraion parameters were applied:

- Takeoff speed = 225 knots.
- Air-Breathing Boosters Landing Gears sized for takeoff: 2.97% of GTOW.
- Turbine engines (when included) sized using methods described by Raymer[7], with takeoff thrust/weight of 0.7.
- RBCC low-speed rockets (when included) sized for thrust/weight at takeoff of 0.7.
- Thermal Protection System (TPS) design point for both vehicles is the staging velocity.
- Rocket Orbiter staging when scramjet computed EISP falls below approximately 700 seconds (~10,000 ft/s).
- LH2 rocket orbiter ascent to 50nm X 100 nm transfer ellipse after staging; OMS engines circularize 100nm LEO orbit.

♦ All Booster Stages are recovered with a turbojet fly-back system and returned to launch site.

6.1.2. TSTO HTHL Turbojet Booster with Air-Breathing Orbiter

The next configuration, shown in Figure 6.2, is also a horizontally launched vehicle. The first major difference in this configuration versus the previous one is the relocation of the hypersonic propulsion components from the booster stage to the upper stage orbiter.

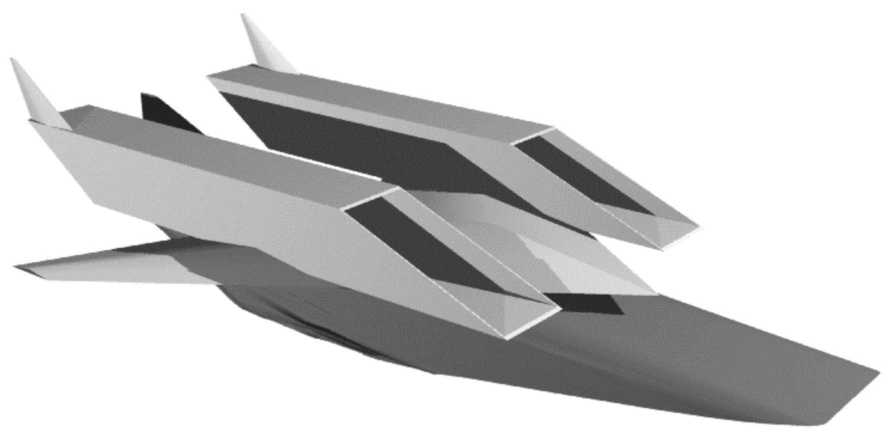


Figure 6.2 HTHL Supersonic Turbojet Booster / Upper-Stage Hypersonic Air-Breather

In the figure, the first stage booster is shown on top, with the upper stage scramjet slung beneath it. The transfer of the ramjet/scramjet to the upper stage relegates the booster to simply providing the low-speed propulsion segment from takeoff to ramjet start; which, for this configuration, is provided by traditional turbine engines. The decoupling of the low speed propulsion cycle from the hypersonic elements removes the integration problems of accomodating both the turbine and scramjet flowpaths and a more traditional turbine inlet geometry may now be incorporated for the booster vehicle. The booster's exposure to high heating environments is also greatly reduced. The combined vehicle system takes off and accelerates until the upper Mach limit of the booster's turbines when the upper stage orbiter is released and the accelerates under ramjet/scramjet power until point of scramjet cutoff. The orbiter will require integrated ascent rockets from the point of scramjet cutoff to orbital injection. After staging, the booster stage flies a short distance to return to the launch site. Both stages are horizontally landed, maintained and integrated. A major benefit of this configuration is that only one vehicle is present during the high drag and high temperature hypersonic trajectory. Another consideration for this configuration is that the on-orbit vehicle now has a hypersonic vehicle geometry and will be required to survive a re-entry trajectory. One version of this configuration was completed for this study utilizing a 2D hypersonic inlet geometry for the orbiter. An inward-turning inlet geometry version could also be accomodated by this configuration, but has not yet been undertaken. Specific parameters of this configuration are listed below:

- Takeoff speed = 225 knots

- Turbine Booster Landing Gears sized for takeoff: 2.97% of GTOW.
- Turbine engines sized for thrust/weight at takeoff of 0.7.
- Turbine Booster TPS design point is staging velocity.
- Air-breathing Orbiter staging at Mach 4.
- Scramjet cutoff when computed EISP falls below approximately 700 seconds (~14,000 ft/s for 2D RBCC).
- Air-Breathing Orbiter Thermal Protection System (TPS) matched for conditions at scramjet design point.
- LH2 RBCC ascent to 50nm X 100 nm transfer ellipse after Scramjet end; OMS engines circularize 100nm LEO orbit.

6.1.3. TSTO VTHL Rocket Booster with Air-Breathing Orbiter

The final configuration considered as part of this study also places the hypersonic propulsion elements on the upper-stage orbiter, as shown in Figure 6.3. In fact, the hypersonic orbiters of this configuration are of the same setup as those used by the previous configuration; the distinction lies in the different approaches employed to accelerate the orbiters to ramjet/scramjet start.

Figure 6.3 VTHL Rocket Booster / Upper-Stage Hypersonic Air-Breather

This configration uses a reusable rocket booster to provide the required low-speeed propulsion segment and, unlike the previous two configurations, is vertically launched. The rocket booster uses liquid hydrocarbon rockets to provide propulsion from takeoff until staging. A booster flying this trajectory requires only a minimal amount of TPS. The booster is also staged at a low enough velocity for it to glide back to the launch site without a fly back system. Though launched vertically, the entire system processing flow, except for fueling, would be performed horizontally as with the other configurations in this study. Both inward-turning and 2D inlet geometries were investigated resulting in two versions of this configuration in this study. The following configuraion parameters were used:

- Rocket Booster engines sized for Thrust / Weight at takeoff of 1.4.
- Rocket Booster TPS design point is staging velocity.
- Air-breathing Orbiter staging at Mach 4.
- Scramjet cutoff when computed EISP falls below approximately 700 seconds (~15,500 ft/s for inward-turning inlets, ~14,000 ft/s for 2D RBCC).
- Booster Landing Gears sized for landing: 4.8% of Empty Weight.
- LH2 RBCC ascent to 50nm X 100 nm transfer ellipse after Scramjet end; OMS engines circularize 100nm LEO orbit.

6.2. *TSTO Vehicle Results*

The three vehicle systems described above were all created and setup within the design code. From these systems, the individual parameters and components were changed to create the six vehicles identified. Multiple solution runs were conducted to "close" each vehicle system for the case of 20,000 lb delivered to the 100 nm circular orbit.

6.2.1. Vehicle Gross Takeoff Weight and Scale Comparison

The gross takeoff weights and lengths of these six vehicle solutions are shown in Figure 6.4. The supersonic XB-70 bomber and the Space Shuttle stack are included to provide scale reference.

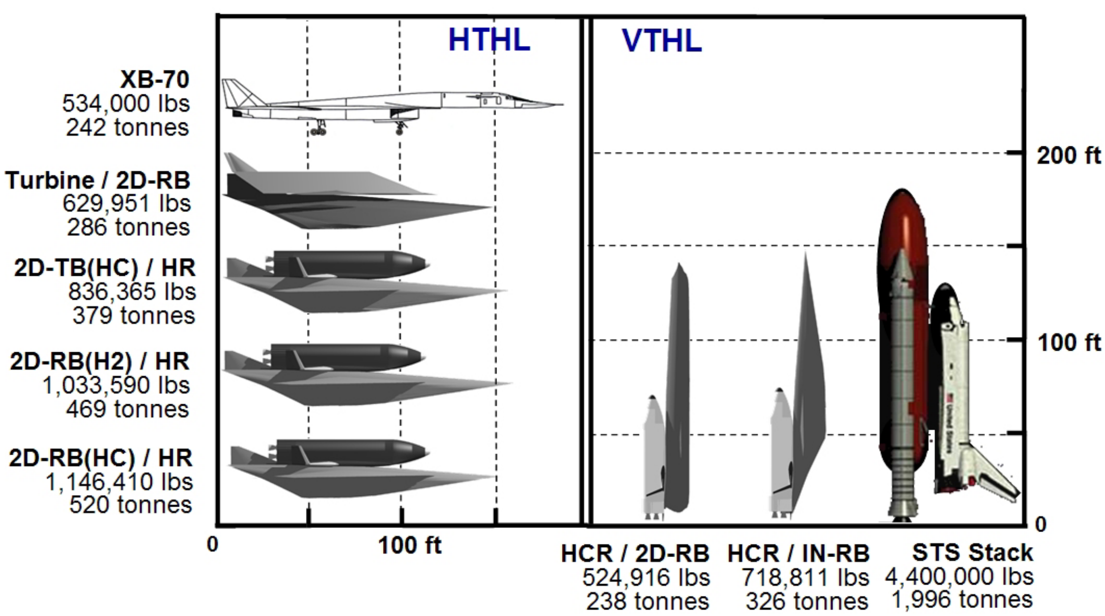


Figure 6.4 TSTO Air-Breathers: GTOW and Scale Comparison

The gross weight of the vehicle represents the fueled weight of the vehicle. Though not as revealing a figure of merit as the empty weight, the gross weight does give quick insight into the scale of the selected vehicle. The figure quickly illustrates the magnitude of these vehicles. Even the lightest HTHL vehicle is of larger scale class than the XB-70, one of the largest and fastest turbine aircraft ever developed. Of the six vehicle systems, the three lightest are those with the ramjet/scramjet engine on the upper stage instead of the booster stage.

6.2.2. Gross Weight Breakdown and Comparison

The weights of the various propellants are the principal constituents of the gross weight. A gross weight breakdown by vehicle and propellant weights is a powerful way to evaluate the different configurations with each other. Such a breakdown is provided in Figure 6.5.

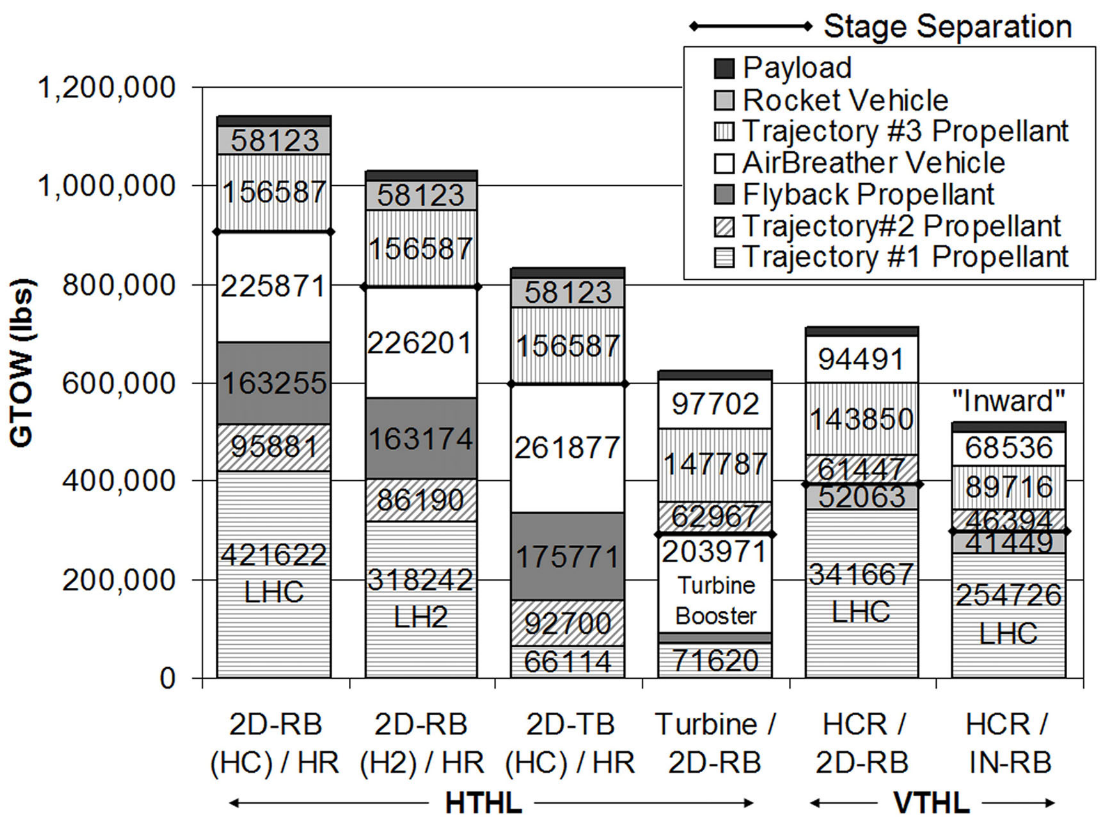


Figure 6.5 TSTO Air-Breathers: Gross Weight Breakdown

The propellant amounts in the figure are divided into one of three propellant trajectory segments. Trajectory segment #1 is the low speed cycle and represents the rocket fuel and oxidizer, or turbine fuel expended during takeoff and initial acceleration. Trajectory segment #2 contains the weight of the hydrogen for the ramjet/scramjet trajectory which is performed by either the first or second stage depending on the configuration. Trajectory #3 for all cases is the weight of the LH2 and LOX required for the rocket ascent to orbit. The individual components within each bar of the figure are arranged in a generally chronological order starting from the bottom; i.e. the propellants/boosters that are located towards the bottom of each bar are consumed/jettisoned before propellants at the top of the bar. The only exception to this trend is the flyback fuel required by the HTHL vehicle to return the booster stage to the launch site, which is consumed after staging.

As shown, the flyback propellant can become a large weight requirement if the booster returns a substantial distance to the launch site as must be done for the three HTHL configurations which make use of ramjet/scramjet booster stages. Both the first and second trajectory segment propulsion requirements have to be sized larger to carry this additional weight along to the staging point. The impact on the HTHL all-turbine booster stage is minimal as it is staged at a much lower mach number and is still relatively close to the launch site. The figure shows that the use of either TBCC or straight turbine propulsion yields a significant reduction in the propellant weight used during the first trajectory segment and therefore lowers the total gross weight of these TSTO configurations. The first segment propellant weights for the two HTHL RBCC vehicles are five to six times the amount for the HTHL TBCC or turbine booster. In considering these differences it should be remembered that the propellant weight of the first trajectory segment will be quickly expended and not carried along very far by the vehicle whereas physical propulsion components such as the turbines or low-speed rockets are part of the vehicle empty weight and will be carried until the booster is staged. Increasing the weight of a later segment increases the sizing of all previous segments that carry it. The upper-stages at the top of the three left bars in Figure 6.5 are the LH2 rocket orbiters. The rocket vehicle weight and trajectory #3 propellant weights are all the same for these three rocket orbiters as they are identical vehicles starting from the same staging altitude and Mach number. The upper-stages at the top of the three right bars are RBCC air-breathing orbiters all starting from the same staging point at Mach 4. Two of these orbiter vehicles have nearly identical weights for second and third propellant segments and empty weight because they are essentially the same vehicle using the same 2D inlet geometry and differing only slightly due to small differences in the weights of their required linking structures to respective and very different booster stages. The third orbiter uses the inward-turning inlet and shows a nearly 30% reduction in second and third trajectory propellant weights and orbiter empty weight versus the 2D geometry orbiters. For each of the six vehicles, the weight of the hydrogen fuel required for the ramjet/scramjet trajectory is quite small relative to the total gross weight thus illustrating one of the primary benefits of an air-breathing engine. This advantage is mitigated slightly by the large amounts of volume required by the hydrogen fuel.

6.2.3. Empty Weight Comparison

The total empty weights for each of the six TSTO air-breathing vehicle systems are shown in Figure 6.6.

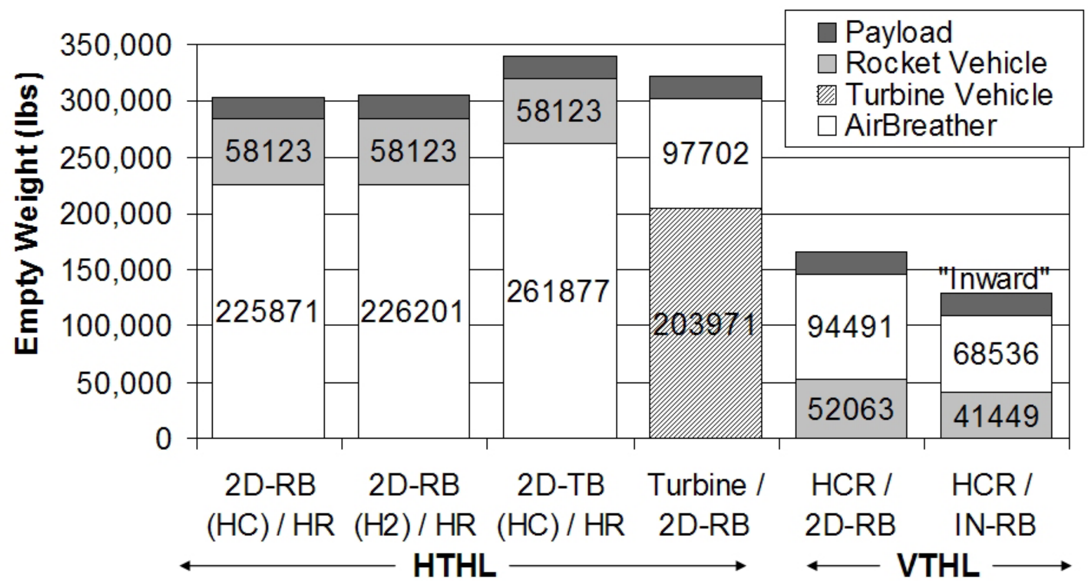


Figure 6.6 TSTO Air-Breathers: Empty Weight Comparison

As may be seen from the figure, the four HTHL vehicle systems (located on the left of the figure) are approximately twice as heavy in total empty weight as the two VTHL vehicle systems. For the three HTHL systems with hypersonic boosters, it is the air-breathing first stage which makes up nearly 80% of the total empty weight while the upper stage reusable rocket orbiters close much smaller. The first stage is also the major portion of the empty weight for the fourth HTHL vehicle (all turbine first stage); however, in this configuration, the hypersonic air-breathing systems are part of the upper-stage orbiter which is under 100,000 lb empty weight. So, while the four HTHL vehicles have roughly the same amount of total empty weight, the empty weight of the hypersonic air-breathing vehicle itself is greatly reduced when it is part of the upper stage. This is an important result as the design, construction, and operation of the high-speed air-breathing technology is the most difficult challenge for any of the configurations in this investigation. Configurations which can reduce the scale of the air-breathing vehicle may therefore become quite advantageous. The VTHL vehicles exhibit this same advantage with their upper-stage air-breathing orbiters. Comparing all six vehicles; the VTHL configurations come in at half the total empty weight of any HTHL configuration. The VTHL air-breather stages are also 60 to 75% lighter than the air-breathing first stages of the first three HTHL configurations.

6.2.4. Wetted Area Comparison

The first stages of TSTO configurations with lower staging Mach numbers are not present during the highest temperature regimes of the trajectory and can therefore manage with less capable TPS. The air-breathing stages need substantial active cooling through the extreme parts of the inlet and nozzle and throughout the combustor. The lower temperature limit passive TPS on the boosters with Mach 4 staging is not stressed greatly during flight and may require minimal, or less frequent, TPS inspection and maintenance. Figure 6.7 compares the wetted areas of all six vehicles broken down into four major TPS types: high and low temperature state of the art passive TPS, future advanced TPS, and actively cooled TPS.

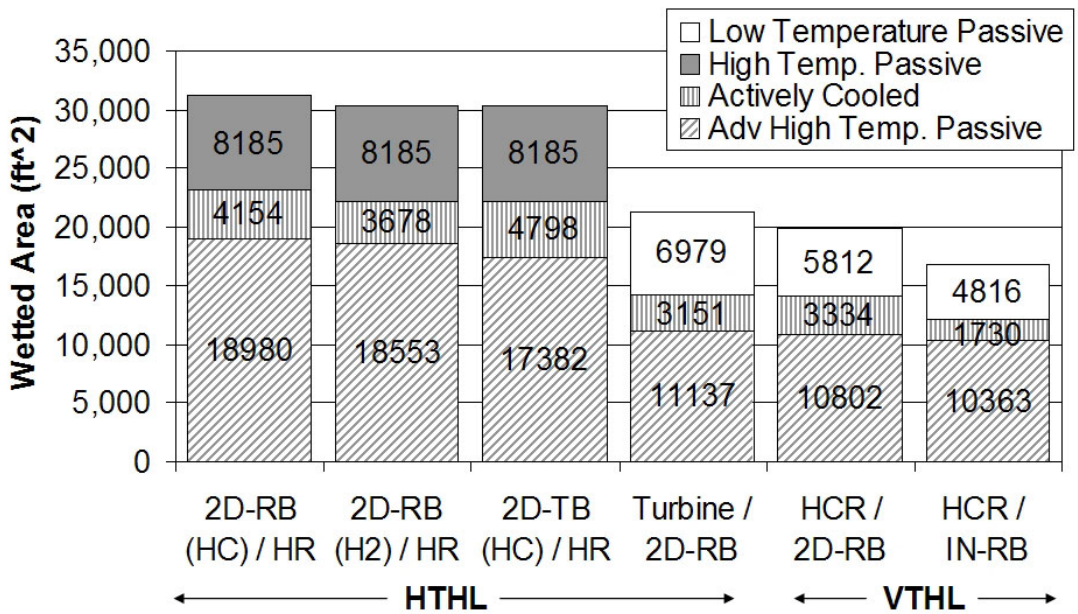


Figure 6.7 TSTO Air-Breathers: Wetted Area and TPS Type Comparison

The hypersonic air breathing vehicles all require advanced high temperature passive TPS over every exposed portion of the vehicle's external surface and internal flowpath except for the flowpath regions that are actively cooled. Therefore, the larger the vehicle, as presented in the previous figure, the larger the amounts of advanced passive TPS and active cooling required. So, the smaller and lighter upper-stage air-breathing orbiters (right half of figure) once again surpass the booster stage hypersonic air-breathers (left half of figure). The three HTHL vehicles with upper stage rocket orbiters are shown on the left half of the figure. As mentioned in the configuration setup, the entire external surface of these rockets must be protected with high temperature passive TPS shown at the top of the bars. Conversely, the rocket boosters used as the first stage of the two VTHL configurations shown at the right of the figure are only attached up to staging at Mach 4 and therefore only require low temperature TPS as they experience no significant heating environment. This low temperature passive TPS shown at the top of the bars on the right is very likely to be more cost and time effective to inspect and maintain than an equivalent amount of high temperature TPS. The same trend is seen in the TPS required for the all turbine HTHL booster. In a effort to reduce the maintenance cost and decrease the turn time of future launch vehicles, the most promising vehicles are those whose solutions make use the least amount of high temperature passive and actively cooled TPS. Taking these assumptions into account, the two VTHL configurations, which already have approximately half the total wetted area of the largest three HTHL vehicles, would exhibit reductions even more than that 50% in refurbishment time and cost.

6.2.5. TSTO Design Traceability to SSTO

The results of Chapter 5 ascertained that there are SSTO air-breathing configurations which may have the potential to improve the accessibility to space by exceeding the abilities of next generation all-rocket systems. However, as has been mentioned, there are great challenges to be overcome in the development of such an SSTO. The technology needs to be further applied and tested before embarking on such a task. The development of the vehicles in this study serves as a first step in ascertaining the functional ability of hypersonic air-breathing technology in less demanding and more forgiving TSTO configurations. With this role in mind it would be prudent to evaluate the air-breathing stages of the three different configurations in this study with the objective of determining which arrangement provides the surest technological foundation from which to initiate an SSTO program. In brief, which air-breathing vehicle is the most similar in application to an eventual SSTO air-breather and would therefore reduce the associated design risk and technological uncertainty. There are some unknowns that would be equally answered by the successful development of any of the TSTO ramjet/scramjet systems in this study such as the sustained operation of a large scale hypersonic propulsion system, vehicle integration issues, etc.

However, there are other SSTO technological questions that are only answered by particular configurations.

One major issue is that of re-entry. A scramjet vehicle is unlike any geometry that has flown a re-entry trajectory. The SSTO scramjet flowpath, while designed to withstand the heating environment of its ascent trajectory, must also be able to withstand re-entry environments. This may require the carriage of reserve hydrogen fuel with which to run the heat exchangers that cool the actively cooled TPS surfaces. The VTHL and HTHL TSTO configurations with upper-stage air-breathing vehicles would require these considerations in their vehicle systems design as these orbiters would also be required to perform re-entry. The HTHL configuration with the hypersonic booster would not address this issue as the air-breathing components never ascend beyond the Mach 10 staging velocity.

Another issue is the high Mach number range of operation for the scramjet engine. A successful and competitive hypersonic SSTO requires the scramjet to achieve as high a velocity as possible before switching modes to the orbital ascent rockets. In the eventual development of an SSTO it will be important to have good data and experience with that flight regime. The HTHL configuration with the hypersonic booster only provides operational data up to its Mach 10 design point to which it is limited by the additional drag of the piggybacked upper stage rocket orbiter. The HTHL and VTHL configurations with upper stage hypersonic orbiters are staged at Mach 4 and accelerate up to around Mach 14 exactly as would be required by an SSTO scramjet vehicle.

Figure 6.8 lists several of the most important operational characteristics and technology certifications that would be required for the successful development of an SSTO air-breathing vehicle and uses them to compare the similarities and differences of different air-breathing stages of the TSTO configurations.

Vehicle Type	SSTO	1st stage AB	2nd stage AB
Cutoff Mach#	14+	10+	14+
On-Orbit Vehicle	Yes	No	Yes
Re-entry	Yes	No	Yes
Scramjet Performance	Yes	Yes	Yes
Integration Issues	Yes	Yes	Yes
Materials	Yes	Yes	Yes
Staging	None	Complicated	Simpler

Figure 6.8 TSTO Air-Breathing Stages: Similarity Comparison to SSTO Air-Breather

These traceability issues indicate that TSTO configurations that employ upper stage air-breathers exhibit greater design similarity with SSTO air-breathing configurations than do the TSTO systems with hypersonic first stages.

6.3. TSTO Air-Breathing Configurations Conclusions

The Air-Breathing TSTO investigation in this chapter considered 6 vehicle systems from three different configurations of rockets, turbines, and hypersonic stages. The mission objective for all vehicles was the placement of 20,000 lb of payload to LEO. These systems were solved and evaluated using several figures of merit. From the results of the work performed during this study the following conclusions may be drawn for each of the three configuration categories as applied to their abilities to improve access to space:

6.3.1. TSTO HTHL Air-Breathing Booster with Rocket Orbiter

- The three vehicles analyzed with this configuration have the largest gross weights, empty weights, total wetted areas, and amounts of active cooling of the six vehicles investigated.
- This configuration requires the largest hypersonic air-breathing stages of the three configurations analyzed.
- Both stages of this configuration are exposed to the highest heating environment of the ascent trajectory. This increases the amount of high temperature TPS required and will lead to higher and longer refurbishment costs and time.

- Complicated high-speed separation maneuver.
- The additional drag of the upper stage rocket orbiter limits scramjet operation to Mach 10.
- The air-breathing booster of this configuration is required to perform a greater than 1000 nm flyback trajectory to the launch site. The additional propellant for the that return must be carried on board all the way to the staging point and triggers a scaling up of the whole first stage system.
- The on-orbit vehicle is a reusable rocket orbiter with a similar geometry as the Shuttle Orbiter and will have an analogous re-entry environment exposure and trajectory. This arrangement; however, does not address the design challenges that will be required for performing re-entry of an on-orbit vehicle with a hypersonic geometry as would be required by an air-breathing SSTO.
- Of the three configurations analyzed, this configuration exhibits the least amount of commonality and design traceability to eventual SSTO air-breather development.

6.3.2. TSTO HTHL Turbojet Booster with Air-Breathing Orbiter

- Low speed separation minimizes use of high temperature TPS on turbine booster stage thereby decreasing the weight as well as the time and cost associated with refurbishment of that stage. The turbine vehicle itself has a large empty weight however.

- Positioning of the ramjet/scramjet propulsion elements on the upper stage decreases the empty weight and wetted area of this air-breathing stage. The upper stage air-breather yields a 60% reduction in the empty weight and a 40% reduction in total wetted area versus the air-breathing booster stages of the previous configuration.
- The air-breathing upper stage accelerates to an approximately Mach 14 scramjet cutoff thus extending the operational depth of detail and performance data of the high speed portions of the scramjet trajectory.
- After staging, the turbine booster performs a short flyback return to launch site. The fuel requirement imposed by this short flight is not significant.
- Once the booster stages at Mach 4, the upper stage air-breather's mission profile and performance requirements are directly analogous to those required by an SSTO air-breathing vehicle. This commonality adds additional relevance and design traceability to the technology that would be acquired during the development of an upper-stage air-breathing configuration.

6.3.3. TSTO VTHL Rocket Booster with Air-Breathing Orbiter

- Low speed separation minimizes use of high temperature TPS on rocket booster stage thereby decreasing the weight as well as the time and cost associated with refurbishment.
- The total empty weight of the two vehicle systems solved using this configuration were roughly half of the empty weight of any of the HTHL systems.
- Upper stage air-breathing orbiters for this configuration are practically identical to the air-breathing orbiters of the previous configuration and exhibit all of the same weight reductions, performance improvements, and technology traceability.
- Difference in this configuration versus the previous one comes down to the selection of a 50,000 lb Mach 4 VTHL rocket booster or a 200,000 lb Mach 4 HTHL turbine booster. A more detailed assessment of the operational abilities and economics of these two configurations is necessary in order to choose between them. Regardless of the choice of low-speed propulsion stage, the data show the upper stage hypersonic air-breathing orbiter to be a superior configuration compared to a hypersonic air-breathing booster.

Chapter 7. Weight Growth Study

During the past two decades, there have been several failed attempts at the development of reusable rocket or air-breathing launch vehicle systems. Vehicle concepts such as NASP, DCX, and X-33 are among those programs cancelled. A contributing cause to the demise of these programs was the impact of vehicle growth arising from inaccurate predictions in the attainable level of technology. This phenomenon was particularly apparent in the NASP program which, by the time of its cancellation, had grown in physical scale many times beyond initial forecasts. The X-33 met a similar fate when the expected propellant tank weight became unachievable due to technology problems with the planned composite tanks. The substitution of heavier more traditional tanks into the nearly complete vehicle would have resulted in a system now unable to meet its mission goals.

The incorporation of a healthy design margin is a widespread approach to addressing such growth problems in launch vehicles and has been used routinely in aircraft design and sizing. However, launch vehicles have a much steeper growth response than aircraft and while a significant design margin may mitigate the growth risk of a multi-stage launch vehicle, even a 50% margin can be insufficient for a single-stage launcher. A successful reusable launch vehicle program must understand and compensate for these growth effects and focus its efforts on both the realistic estimation of utilized technology levels and the targeted improvement of those technologies with the greatest system growth impact. This consideration is doubly important for immature and evolving technologies such as hypersonic air-breathing propulsion.

The work presented in this chapter represents a broad effort to characterize the growth behavior of a wide-ranging suite of potential reusable launch vehicles for access to space. The reference mission for each configuration solution is a 20,000 lb payload placed into a 100 nm Low-Earth Orbit. The study considered all of the configurations presented in this thesis which extend across the spectrum of both SSTO and TSTO air-breathing and rocket vehicles and hybrid combinations of the two and includes both horizontal and vertical launch modes. The goal of this growth study is not to present a single best answer or optimized design, but to gain an understanding of the solution space and identify the configurations and operational modes that exhibit the least amount of design risk and consequently stand a better chance of becoming a programmatic and operational success.

7.1. The Empty Weight Growth Factor

The growth factor is a measure of the scaling response in vehicle empty weight to an increase in the unit weight of the vehicle structure. This increase is often due to a change in the estimation of the corresponding weight of some structural technology; such as a heavier or lighter weight TPS tile type. The growth factor can therefore be used as a measure of the vehicle's response to the technological uncertainty inherent in the development of a future system. A general vehicle scaling reaction to such an increase follows the steps outlined below:

♦ A closed vehicle solution experiences an increase in a structural unit weight.

♦ That percentage increase multiplied by the total amount of that structural component present in the closed solution results in an additional amount of empty weight that must now be carried by the vehicle.

♦ The vehicle solution is no longer closed. The additional weight is a perturbing influence that triggers a scaling up of the vehicle solution in order to re-close the vehicle.

♦ As the vehicle grows in response to the weight change it must now do so with a correspondingly higher unit weight.

♦ This double impact causes a much larger change in the re-closed vehicle's empty weight versus the original empty weight than just the addition of the perturbing change in structure weight.

♦ The growth factor is obtained by differentiating the empty weight scaling equation6 with respect to the weight change and is the slope of the delta weight / delta weight curve at the point of the vehicle solution.

Vehicles that are highly sensitive to small changes, such as SSTO rockets, have extremely high growth factors. This makes it nearly impossible to set the scale and size of the vehicle unless there is a near perfect certainty in the performance and technology of the system. Other vehicles, such as TSTO rockets have low growth factors; indicating a vehicle system that more easily absorbs design or technology changes during the development program without excessive increases in size and weight. A program with such a vehicle is many times more likely to be successful at incorporating the actual design numbers once the vehicle design has been frozen. A high growth factor does not necessarily invalidate a particular design; it is just a measure of how much more certain you must be in your solution parameters if you want to be successful with that design.

7.2. *Growth Investigation Setup*

7.2.1. Selected Baseline Vehicles

The baseline versions of the configurations analyzed for this study were setup and solved during previous investigations described in the previous chapters of this thesis. Figure 7.1 identifies these configurations and their baseline gross weights (the STS and XB-70 Valkyrie are included for scale reference). As seen from the figure, the study investigated eighteen vehicle configurations; nine SSTO and nine TSTO. All of the SSTO vehicles were hypersonic air-breathing vehicles differing by inlet type, propellant selection, low-speed propulsion cycle, and takeoff mode. The TSTO configurations included three pure rocket systems as well as air-breathing vehicles combined with either an upper stage rocket orbiter or first stage rocket booster. The air-breathing vehicles used either an inward-turning "IN" inlet or more traditional wedge "2D" type inlet geometry. The low-speed propulsion cycles for all air-breathers was provided by either integrated rockets "-RB" or turbines "-TB" operating on hydrogen "(H2)" or hydrocarbon "(HC)" fuel. One HTHL vehicle uses a pure turbine booster as a first stage. The TSTO notation in the figure is listed as Stage1 / Stage2.

Figure 7.1 Investigated Configurations: Baseline GTOW and Scale Comparison

7.2.2. Determination of Growth Response

To find the growth response, an empty weight sizing equation is needed for each launch vehicle system. This behavior was determined for each vehicle configuration by doing the following:

- ♦ Each vehicle system was re-closed in HySIDE following the procedure outlined above for percentage increases in the total baseline structural (empty) weight from -10% to +10%.
- ♦ An empty weight sizing equation was obtained for each vehicle system by curve fitting through the re-closed solution points. This curve is the change in actual empty weight vs. the initial change in perturbing structural weight.
- ♦ By differentiating this equation with respect to the corresponding initial change in structural weight, the vehicle Growth Factor was obtained at each data point.

Once obtained, the Growth Factor may also be used for quickly performing multiple individual system component technology assessments without the need to re-solve each system separately. Thus employed, the growth factor is a very powerful way to determine configurations that pose less of a design risk. Once a particular vehicle's scaling behavior is understood, it can be coupled with further analyses to determine an appropriate design margin. Livingston[28] has combined the growth factor process with defined uncertainty bands on the vehicle technology to determine the growth point required to achieve an 80% probability of successful closure.

7.3. Growth Factor Results

The eighteen vehicle configurations were all re-solved for empty weight percentage changes of -10%, -5%, +5%, and +10% thus representing an additional seventy-two closed vehicle solutions in addition to the original eighteen baseline closures. The discussed measures of merit were determined for each solution point and are presented in the following section. In each of the remaining figures, each individual vehicle system is shown at the five solution points such that the general trend in each is readily estimated. The data thus presented yields valuable insight into a broad range of possible vehicle growth both positive and negative. If it is determined that the baseline technology assumptions utilized for this study are too optimistic, one need only shift up to a higher +% solution point on each vehicle in order to re-assess the impact of a more conservative performance estimate.

The next six figures show the growth factor versus empty weight trends for each major configuration category. The five solutions for each vehicle are represented as points on the figures with trend lines connecting them. The filled in symbols represent the baseline solution; the two open symbols below this point are the -5% and -10% solutions and the two open symbols above the baseline point are the +5% and +10% solutions. There are a few configurations whose closure points extend off above the scale of the figure axis in which case only the negative percentage solutions may appear. The shape of the symbol is tied to the type of configurations; circles for inward-turning geometries, squares for 2D geometries, and triangles for pure TSTO rockets. For clarity, the trends are shown in configuration groups first before being shown all together. A thumbnail image representative of the configuration type is also included on each figure.

7.3.1. SSTO VTHL Air-Breathers

Represented in Figure 7.2 are the growth factors vs. empty weights for the four SSTO vertical takeoff air-breathing configurations. The configurations differ by inlet type and low-speed rocket propulsion segment fuel selection.

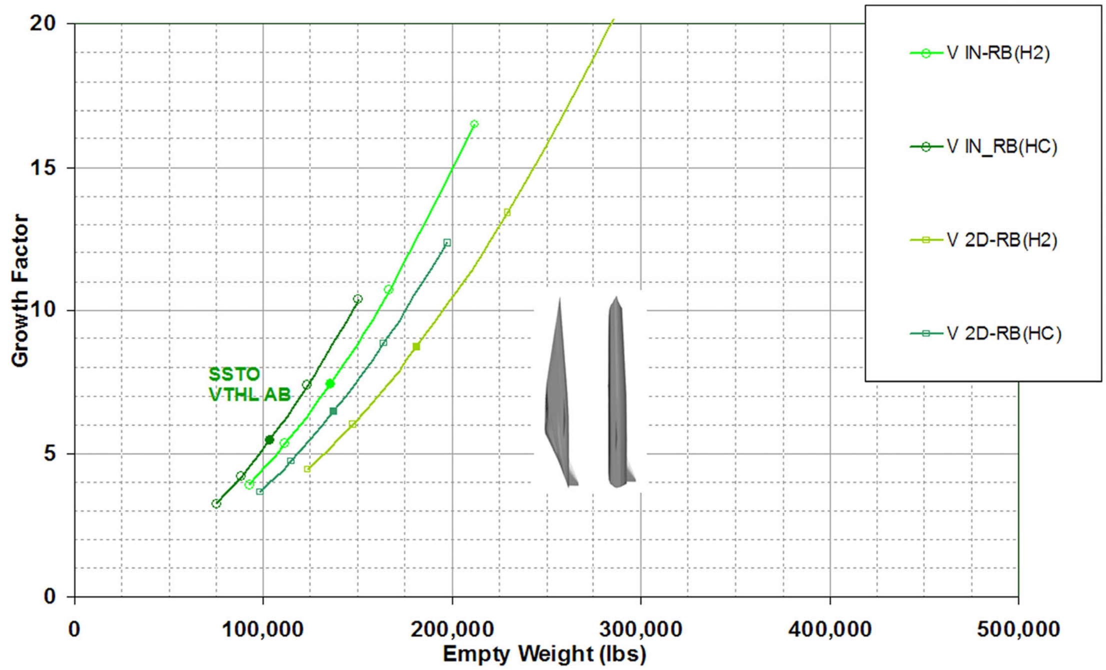


Figure 7.2 Growth Factors vs. Empty Weight: SSTO VTHL Air-Breathers

The figure shows that the VTHL inward-turning air-breather with a hydrocarbon fueled low-speed propulsion segment has the lowest baseline growth factor and empty weight of the four configurations. The all hydrogen versions have slightly higher baseline growth factors. This difference becomes magnified as the solutions are run at the +5% and +10% cases. As seen in the figure, the distance between the baseline solution point and the +5% point is greater for the vehicles with higher baseline growth factors than for those with lower baseline growth factors. The higher growth response necessitates further scaling in order to re-close the vehicle. This behavior is only amplified when considering the distance to a further closure point. For example, at the +10% point, the inward-turning (HC) vehicle has increased its growth factor by 5 and its empty weight by 50,000 lb while the all hydrogen 2D configuration has increased more than 12 in growth factor and over 100,000 lb in empty weight and is almost off the chart in this representation.

7.3.2. SSTO HTHL Air-Breathers

Figure 7.3 shows the same types of SSTO configurations, but adapted for horizontal takeoff.

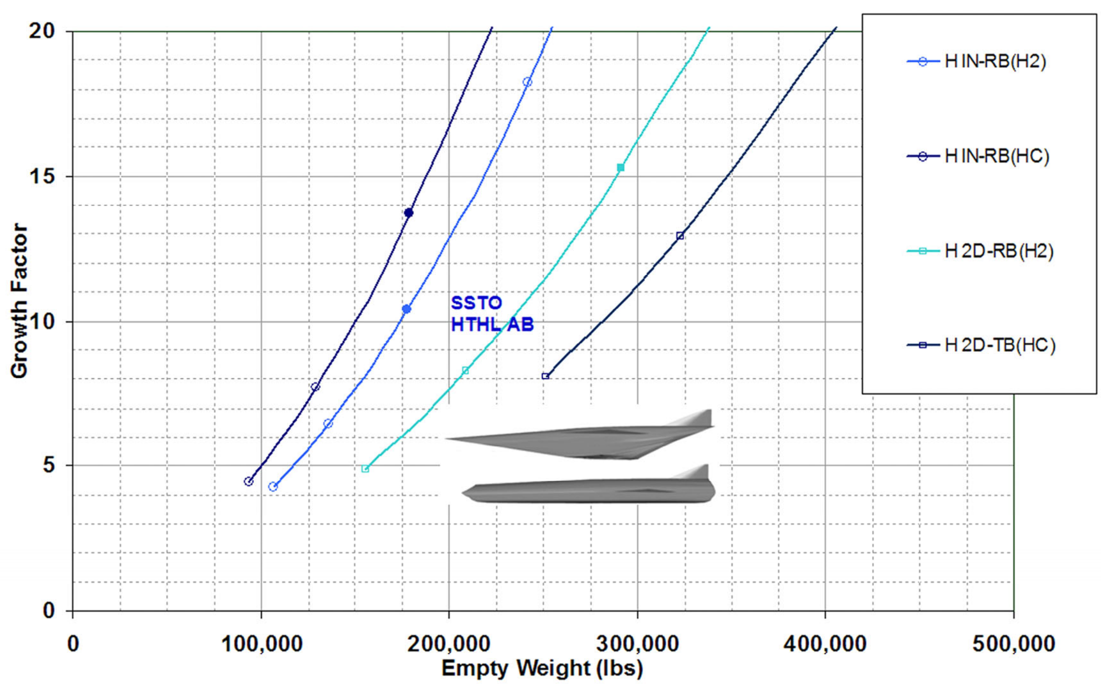


Figure 7.3 Growth Factors vs. Empty Weight: SSTO HTHL Air-Breathers

The baseline solution points for the HTHL configurations have shifted quite noticeably towards higher values of growth factor and empty weight. The higher growth factors cause small differences in the configurations to be magnified thus resulting in a sparser concentration of the baseline solutions than was seen for the VTHL vehicles. This accelerated growth response is due to the horizontal takeoff mode of these configurations. Both the wings and landing gear for an HTHL vehicle are sized with respect to the vehicle gross weight. As the gross weight increases these two sub-systems increase at a faster rate than equivalent systems on VTHL vehicles which are sized for the smaller empty weight increase. The larger wing also results in increased drag losses during the high-speed ascent portion of the hypersonic trajectory. This is also the reason why the use of hydrocarbon fuel in the low-speed rockets utilized by some of these configurations now causes an increase in growth response. The lower performance hydrocarbon fuel drives up the gross weight of the vehicle and thus enters into the wing/gear scaling problem afresh. These factors combined together cause the HTHL baseline solutions to close at higher values such that these vehicles are already exhibiting a nearly runaway scaling response at the +5% closure point. The poorest performer of the four HTHL vehicles shown is the SSTO air-breather with integrated turbines for low-speed propulsion. Its baseline point has a very high empty weight and growth factor and doesn't even appear on this chart, though it's lower -5% and -10% closure points do.

7.3.3. TSTO Rockets

The TSTO rockets are now considered and their solutions are shown in Figure 7.4. The effect of staging on growth response is quite visibly communicated by the concentrated solutions shown.

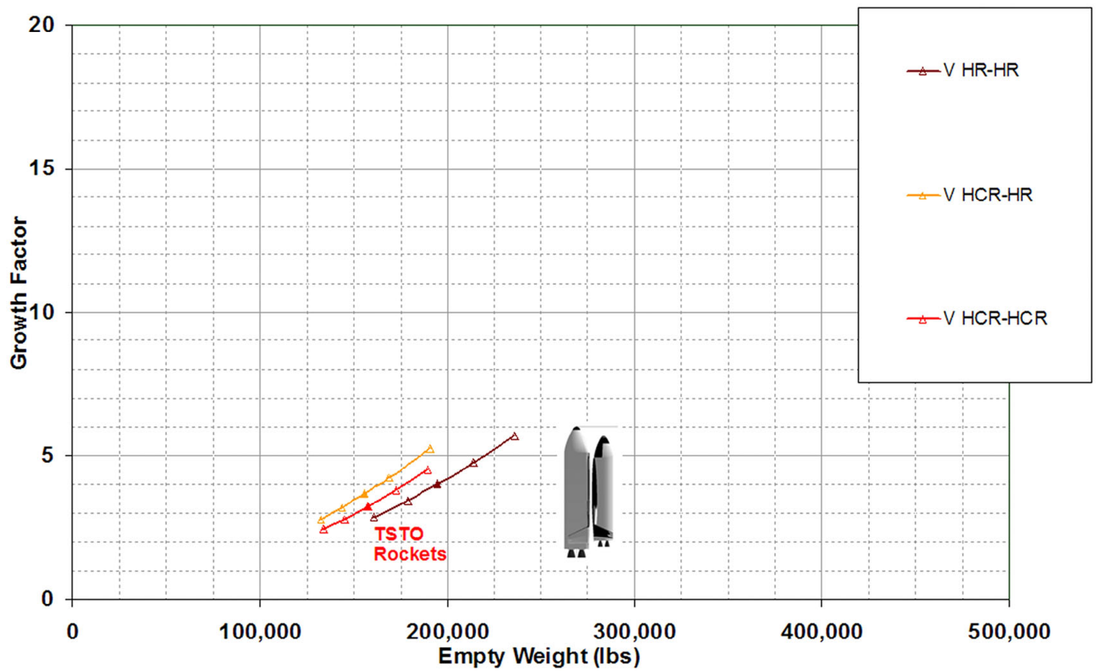


Figure 7.4 Growths Factor vs. Empty Weight: TSTO Rockets

The decreased growth response is a function of the performance benefits of staging and not the use of rockets (SSTO rockets have much higher growth factors than the SSTO air-breathers that were just presented). The empty weight of the three vehicles varies by only ~80,000 lb across the whole range. The smaller changes are indicative of a more robust system that is better suited to absorbing moderate changes in weight and therefore exhibits less design risk. Due to the subdued growth behavior of these configurations, there is very little variation among the three vehicles even though their propellant configurations are quiet different.

7.3.4. TSTO HTHL Air-Breathers / Rockets

Figure 7.5 shows two additional TSTO categories that employ either HTHL air-breathing boosters with upper stage rockets (three vehicles), or an HTHL turbine booster with an upper-stage hypersonic air-breather (one vehicle). The TSTO Rockets from the previous figure remain for comparison.

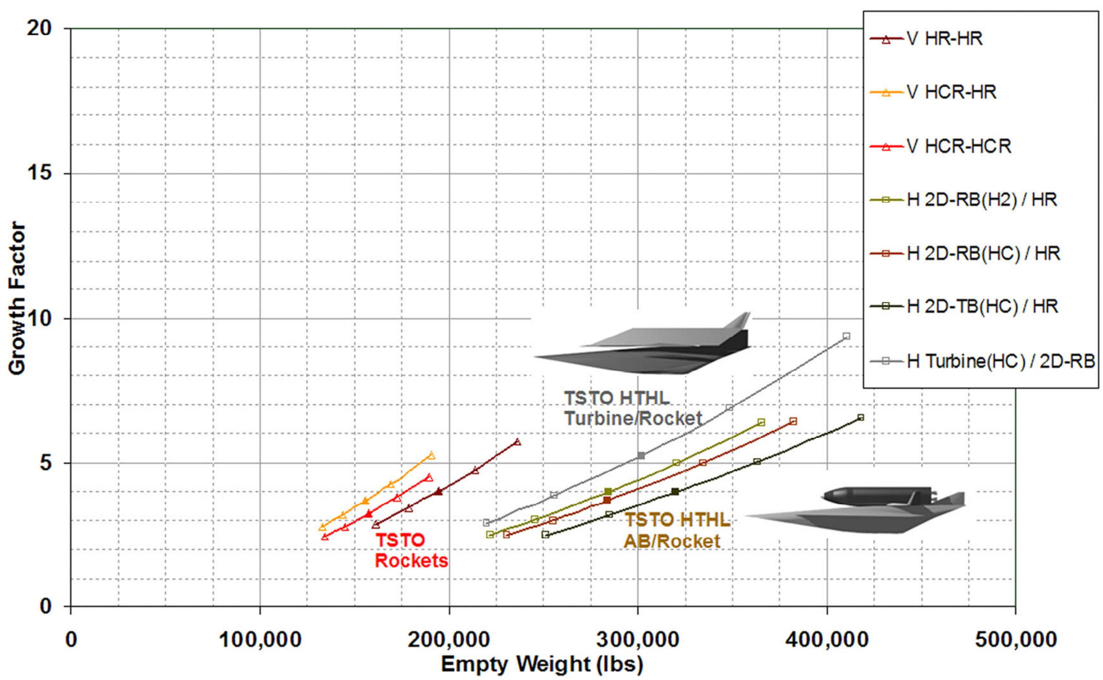


Figure 7.5 Growth Factors vs. Empty Weight: TSTO HTHL Air-Breathers / Rockets

Once again, the use of two stages moderates the scaling response; however, the combined empty weight of the systems using air-breathing stages is double the TSTO rockets. The vehicles show a larger spread in the location of the different closure points, but are still more concentrated than the SSTO HTHL air-breathers. Though these configurations only increase a few point in growth factor up to the +10% case, it is important to note that they have gained ~100,000 lb in empty weight at this point.

7.3.5. TSTO VTHL Air-Breathers / Rockets

Figure 7.6 shows the final two configurations: the vertically launched, rocket boosters with upper stage air-breathers.

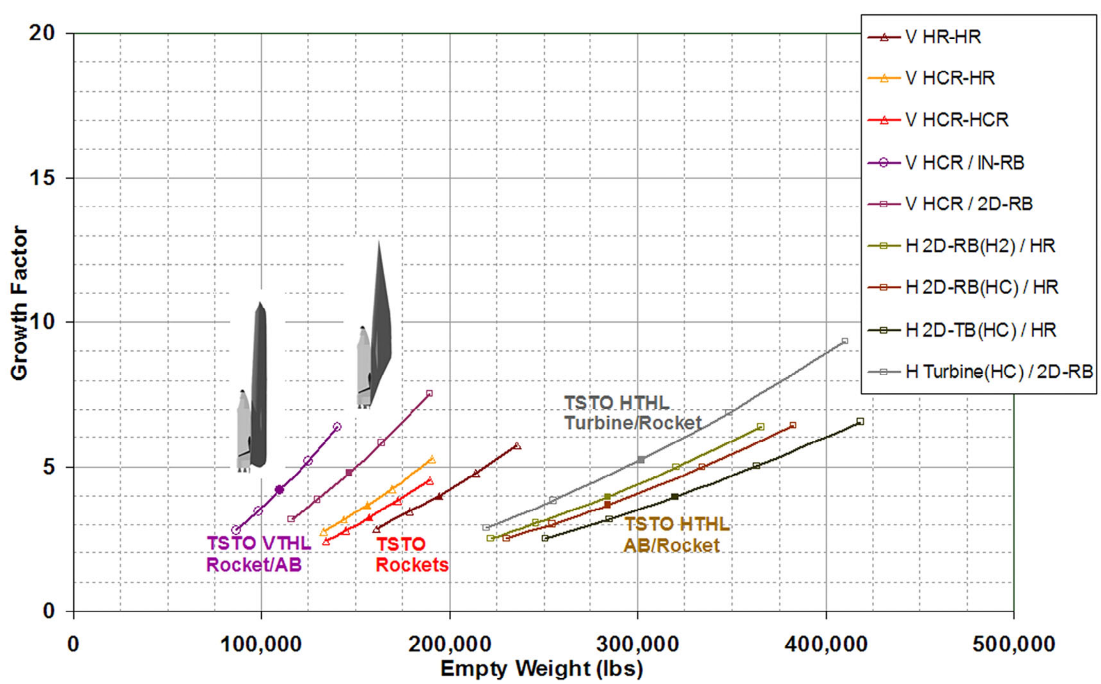


Figure 7.6 Growth Factor vs. Empty Weight: TSTO VTHL Rockets / Air-Breathers

These vehicles are less than half the empty weight of the previous HTHL TSTO vehicles. These two VTHL configurations also show fairly low growth factors and scaling response to growth; however, they have much steeper trend lines. This may lead to the erroneous conclusion that these vehicles are scaling faster than their TSTO HTHL counterparts. The opposite is actually true; the steeper trend indicates less resulting empty weight growth from the same scaling response. The actual +5% solution point for both the VTHL and HTHL configurations is at a growth factor of 5, so both actually experienced the same growth factor increase but with very different outcomes in terms of empty weight response.

7.3.6. Overview of All Configurations

All of the configurations are shown together in Figure 7.7. As evident in the figure, different configurations, even when run for the same payload and mission, can have wildly different growth behaviors.

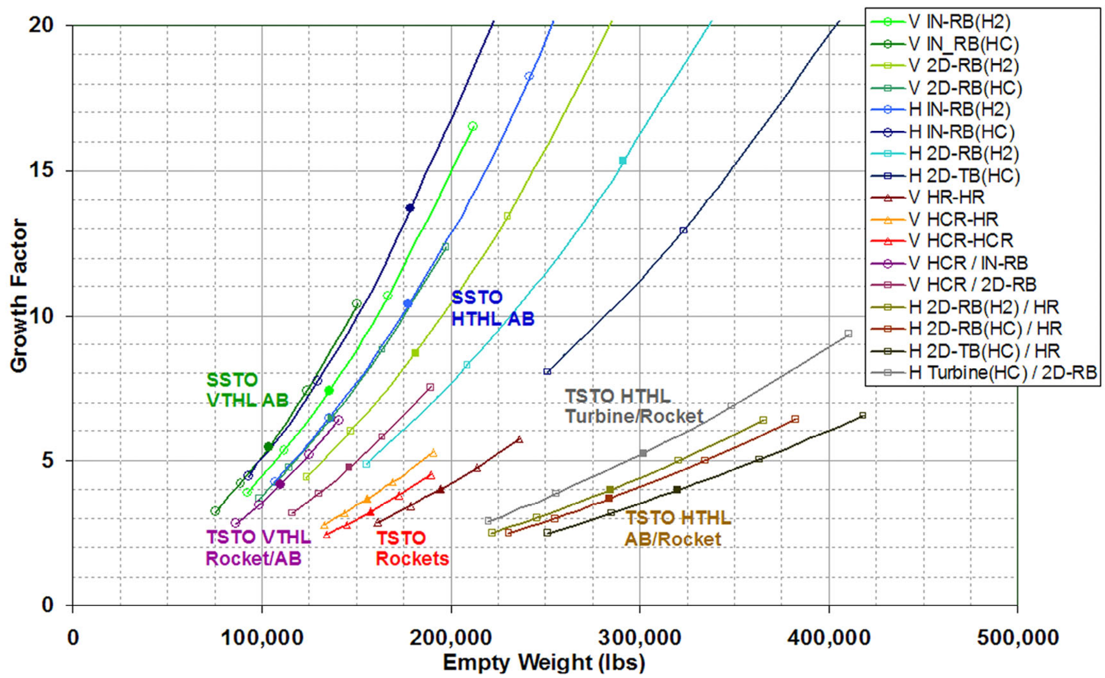


Figure 7.7 Growth Factor vs. Empty Weight: All Configurations

It is interesting to note how the various combinations of different propulsion technologies, operational modes, and staging arrangements cluster into different areas of the figures. For example, the figure clearly shows that the SSTO vehicles have higher baseline growth factors than TSTO vehicles. They also scale up faster in response to growth as evidenced by the greater distance between successive growth points. In terms of empty weight, both SSTO and TSTO vertical takeoff configurations come in at much lower empty weights than their horizontal takeoff equivalents. The empty weight of the pure rocket vehicle systems sits right in between.

7.4. Growth Figures of Merit

The next four figures show the results of each closure solution for the general figures of merit chosen for this study. For the following figures, results are only presented for the best two vehicles from each general configuration with the exception of the SSTO HTHL air-breathing vehicles where three vehicles were presented in order to show the results of the SSTO turbine based vehicle. The results are presented in bar charts with the vehicle closures for the -10% case on the front row, and the +10% case on the back row. Each bar is labeled with the actual solution point data. There is no positive growth data for the SSTO HTHL turbine based vehicle on the far right of the figures as that configuration was impossible to close at even the +5% growth case. The +10% solution point for the SSTO HTHL 2D hydrogen rocket based vehicle is not shown due to blowing up in a similar fashion. A vehicle thumbnail image is included to represent each configuration category and to provide ready identification of each group of data.

7.4.1. Growth Factor

Figure 7.8 is another representation of the growth factor across the different closure solutions for the best two vehicles in each configuration category.

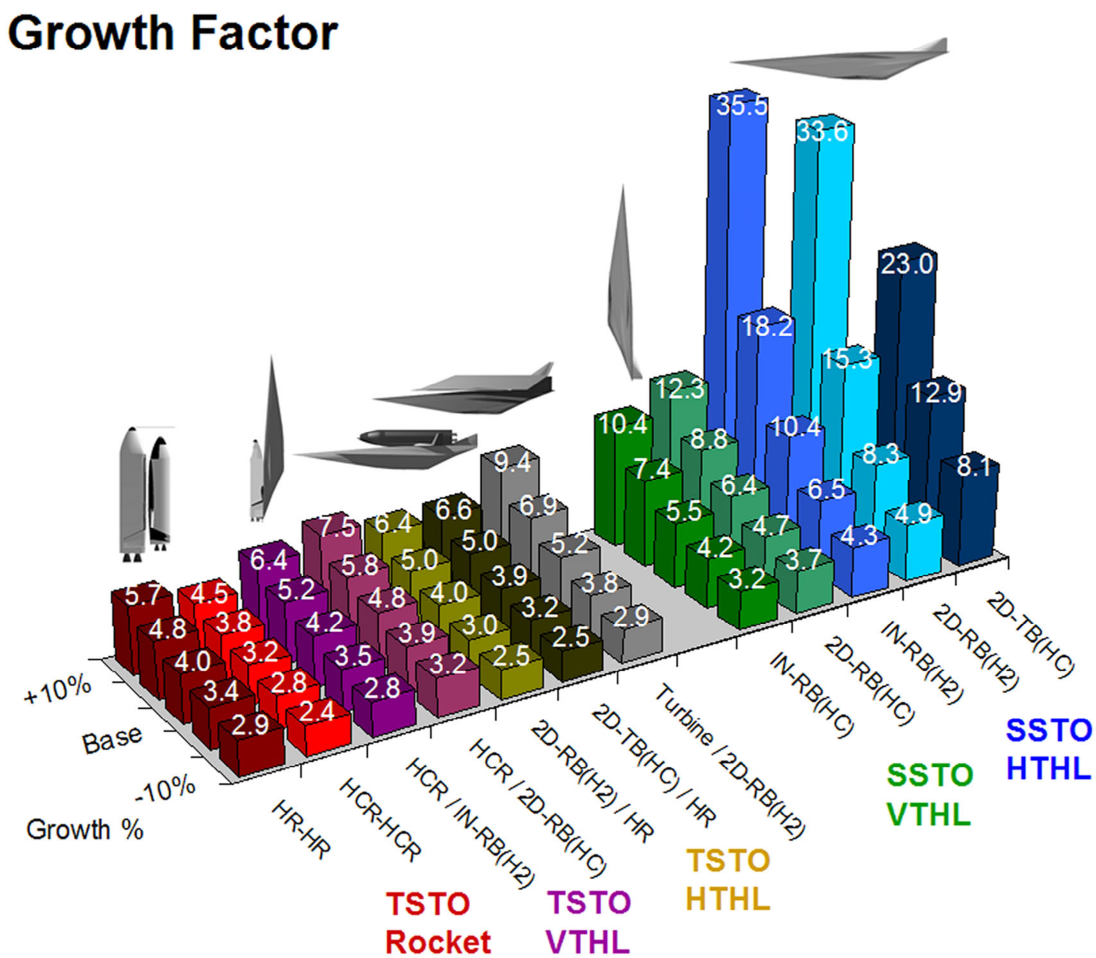


Figure 7.8 Empty Weight Growth Factors

In the figure, TSTO configurations are to the right, and SSTO configurations are to the left. This figure again addresses the low growth factors of TSTO configurations versus SSTO. It should be noted; however, that the SSTO VTHL configurations are not really all that much higher considering that they are SSTO vehicles. Conversely, the SSTO horizontal vehicles exhibit a severe scaling response to growth. The SSTO turbine based vehicle is particularly unmanageable. However, if meaningful improvements in air-breathing technology could be achieved, then it may be possible to close the SSTO HTHL vehicles closer to the much more reasonable -10% solution. At that point, the differences between the VTHL and HTHL modes would be much smaller and the application of more specific criteria could be used to select between the two. The growth factor data suggests that the development of an immature technology such as hypersonic propulsion should first be applied in a more forgiving TSTO configuration to gain experience and develop the technology and then apply that understanding to the SSTO, hopefully achieving the lower closure point.

7.4.2. Empty Weight

The amounts of total vehicle empty weight for each system are shown in Figure 7.9.

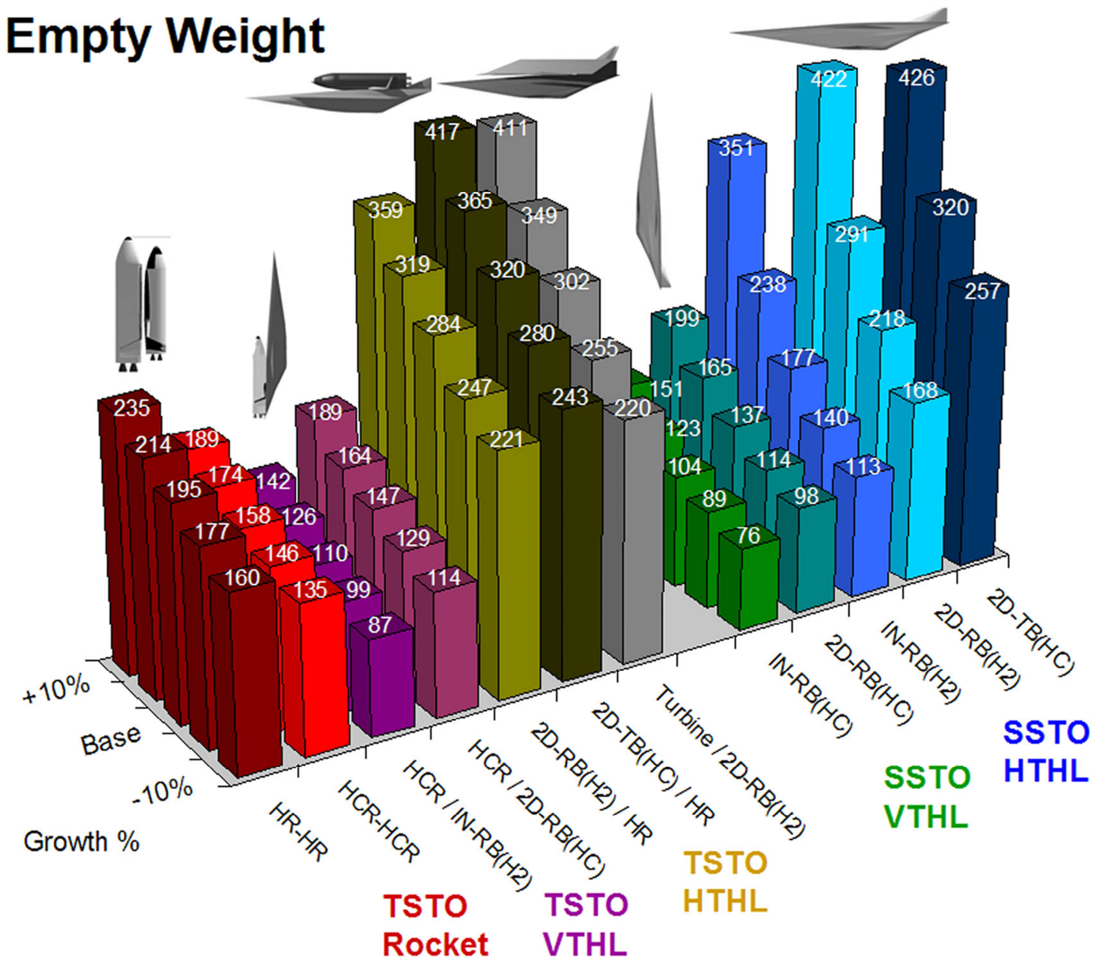


Figure 7.9 System Empty Weights (klb)

The empty weight results for the TSTO vehicles are drastically different from each other. The three highest empty weights for the TSTO vehicles are for the two HTHL configurations and they are often double the amount for the two TSTO VTHL configurations. A more detailed analysis of the causes of the differences between these configurations is contained in Reference 5. The highest empty weights in the SSTO category are also attributed to the HTHL vehicles which, due to higher growth response, can become nearly three times larger than some SSTO VTHL vehicles. The differences between vertically and horizontally launched SSTO vehicles have been extensively addressed in previous chapters. An important point to remember is that not all empty weight is the same. The actual cost "pound for pound" of a rocket vehicle's empty weight is going to be more economical than a pound of air-breathing empty weight. Considering this, the impact of the pure rocket's moderate empty weight on cost is greatly reduced. The same effect would also be seen for the other TSTO configurations which would also be slightly reduced as each has a rocket booster stage or upper-stage. With all of these considerations taken into account, the vertically launched SSTO and TSTO air-breathers, and the pure rockets are the best configurations in terms of total empty weight. Horizontal configurations are much heavier. Another insight is the effect on air-breathing configurations of the propulsion system selected for low-speed flight until ramjet start. The three different configurations utilizing turbines for this low-speed trajectory segment have the three highest empty weights of all the configurations studied.

7.4.3. Wetted Area

The total wetted area for each vehicle is represented in Figure 7.10. The trends seen for wetted area follow the same patterns as those observed for the empty weight.

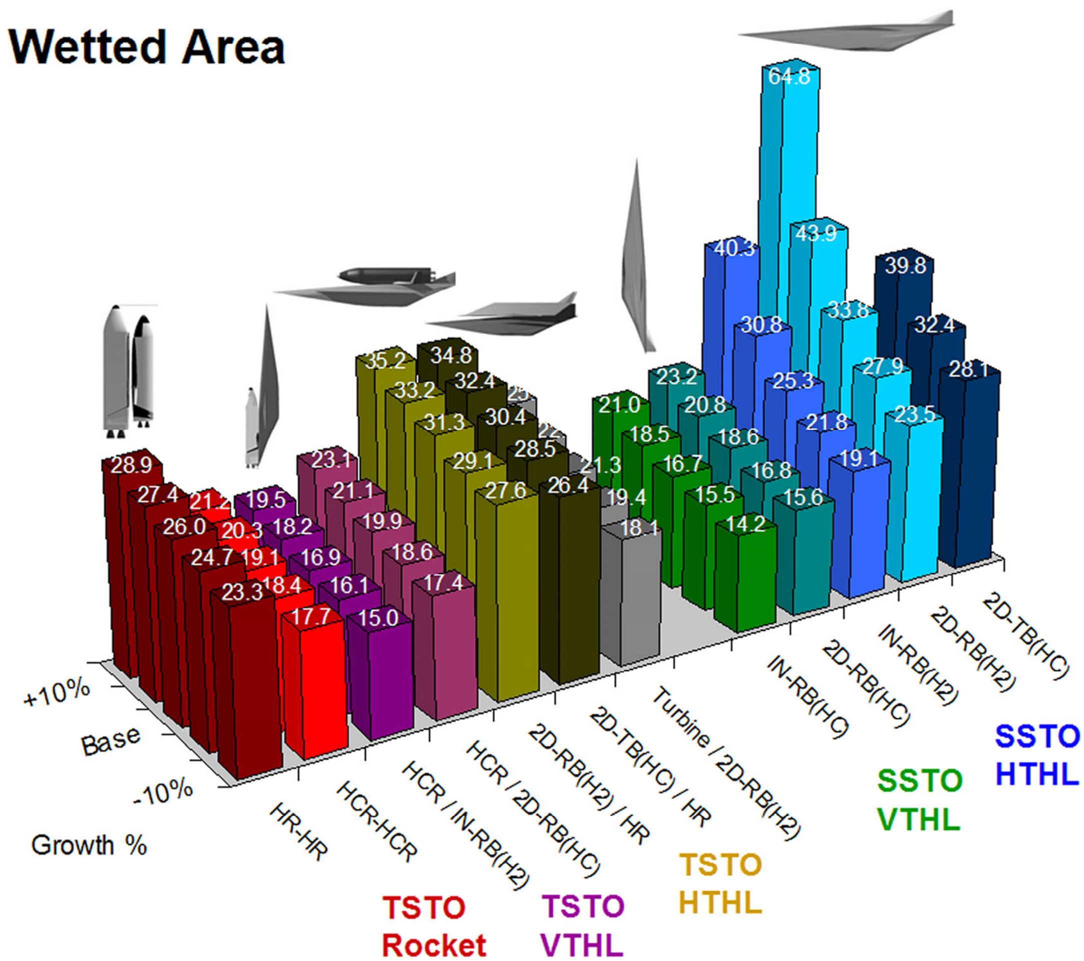


Figure 7.10 Total Wetted Area (kft^2)

As mentioned previously, the wetted area is a strong driver for the amount of maintenance and refurbishment costs and turn time for a reusable launch vehicle. As with empty weight, not all wetted area is the same. For example, the rockets used as first stage boosters never see any substantial heating and therefore get by with much less capable TPS. In contrast, the hypersonic air breathing vehicles all require advanced high temperature passive TPS over every exposed portion of the vehicle's external surface and internal flowpath except for the flowpath regions that are actively cooled. Therefore, the larger the vehicle the larger the amounts of advanced passive TPS and active cooling required. To minimize the maintenance cost and turn time of future launch systems, the most promising vehicles are those with the least amount of high temperature passive and actively cooled TPS. As seen in the figure, the VTHL SSTO and TSTO vehicles have the least amounts of total wetted area and would also have less active area than the other, larger HTHL air-breathers.

7.4.4. Gross Weight

The final measure of merit is the vehicle gross weight shown in Figure 7.11.

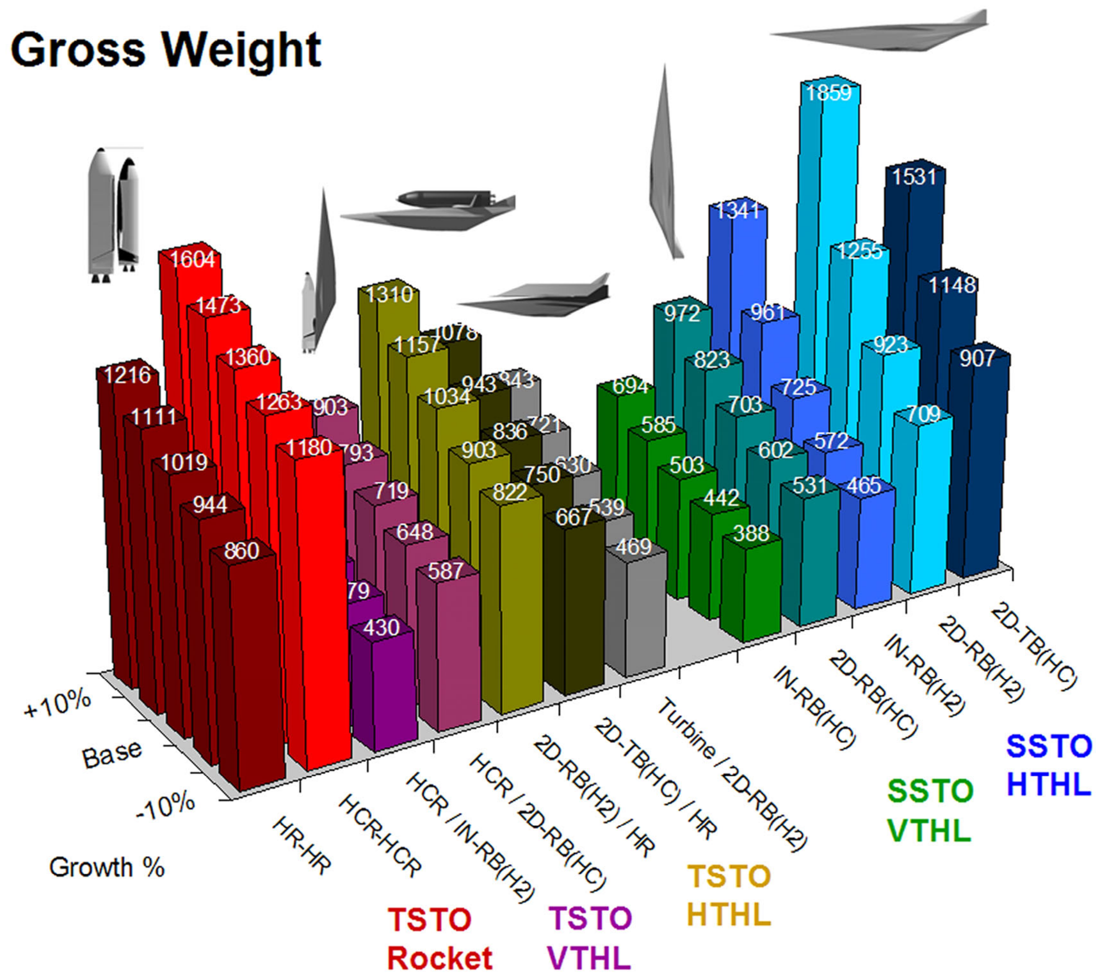


Figure 7.11 Gross Weights (klb)

This is one figure of merit where the pure rockets come out fairly high due to their higher propellant fractions. The gross weights of some of the HTHL SSTO vehicles have exceeded the assumed runway bearing load limitation of 1.5 million lb for some of the closure solutions. At +10%, all SSTO HTHL air-breathers are above this limit with the exception of the all hydrogen, inward-turning vehicle. The SSTO HTHL turbine based vehicle is right at the limit already for its baseline case. These solutions were all for 20,000 lb payload to

LEO. It is easy to foresee from the trends in this figure that any increase in that payload would invalidate all of the HTHL vehicles at any positive growth percentage. The SSTO and TSTO VTHL vehicles have the lowest total gross weights of all the vehicles. An interesting thought for an SSTO VTHL launcher is the lack of a vertical equivalent to the gross weight limit applied to the HTHL vehicles. This means that the lower growth factor and gross weight VTHL air-breathers could be closed for payloads much larger than the 20,000 lb assumed for this study without limitation, so long as the air-breathing technology is proven. Such a vehicle could provide heavy lift at greatly reduced gross weights, and empty weights compared to traditional rockets.

7.5. Growth Study Conclusions

The growth investigation of this chapter considered 18 vehicle systems covering many different configurations of air-breathers and rockets and performed a broad growth investigation to characterize the scaling behavior of each vehicle system. The general growth conclusions that may be drawn as a result of this study are listed below.

7.5.1. TSTO Rockets

- The use of staging greatly reduces the scaling behavior of multi-stage vehicle systems.
- The three rocket vehicle solutions for this configuration have very similar growth factors and empty weights
- TSTO rockets have low amounts of empty weights and wetted area.
- Rocket empty weight requires less technology development than air-breathing structure and will therefore be more economical "pound for pound."
- Rockets have large gross weights versus most of the air-breathers considered.

7.5.2. VTHL SSTO and TSTO Air-Breathing Configurations

- The use of staging also benefits the TSTO air-breathing vehicles both VTHL and HTHL.
- The VTHL air-breathing SSTO and TSTO configurations are the top performers in each of the figures of merit except for growth factor.
- Compared to the horizontally launched air-breathers, these vertically launched configurations appear to be more economical and represent less design and programmatic risk at any scaled closure point.

- If air-breathing technology fails to mature to the level of the baseline assumptions, the VTHL configurations are the only realistically achievable SSTO vehicles at greater growth percentages.
- The rocket boosters of the TSTO VTHL are not exposed to the high heating environment that will be seen by the upper stage rockets of the TSTO HTHL configurations and will therefore be much more economical to design, procure, and turn-around between launches.
- VTHL vehicles have no bounds on their gross weight and may therefore be successfully scaled up for larger payloads than the 20,000 lb used in this study.

7.5.3. HTHL SSTO and TSTO Air-Breathing Configurations

- While the TSTO HTHL vehicles have fairly moderate scaling behavior, the horizontal SSTO vehicles' growth scales rapidly.
- For increased growth percentages, most HTHL SSTO vehicles become un-closable.
- The HTHL SSTO vehicles are likely limited to a maximum payload in the neighborhood of 20,000 lb due to the vehicles' gross weight proximity to the runway bearing load limit.

- HTHL TSTO vehicles have much higher amounts empty weight and wetted area than the VTHL TSTO air-breathers.
- If there exist mission or operational requirements that would necessitate a horizontal launch vehicle, acceptable SSTO solutions could be found if the maturing level of hypersonic air-breathing technology can reach the -10% levels used as part of this growth study.

Chapter 8. Payload Weight Trade Study

The eighteen vehicles that have been presented in the previous chapters have all been solved for a payload requirement of 20,000 lb carried to LEO. This chapter reports the findings of a payload weight trade study that was performed which increased the payload size for many of the most promising vehicle configurations. There are several valuable insights that may be garnered as a result of such a study. First, the behavior of the trends that have been identified thus far for the baseline payload can now be evaluated across a range of payload requirements. Second, having information on a particular configuration at multiple payload points, allows the simultaneous comparison of that vehicle with different existing launch vehicles at their own respective payload classes. Finally, the relative position of the vehicle solutions ranked by the applied figures of merit might shift from that of the baseline when the payload is increased. Of specific interest, is whether the trends in maintenance cost favor a certain vehicle configuration at a particular payload weight. The cost of maintenance, expressed in maintenance man-hours, is one of the figures of merit outlined in Chapter 2, but was first applied in the present chapter to the vehicles for both baseline and increased payload cases.

8.1. *Payload Growth Setup*

Performing the payload trade study required re-closing each selected vehicle within the design code for each new payload weight requirement. The only input parameters that needed changed were the values for the payload weight and payload volume. Payload volume was increased to maintain the same payload density that has been uniformly used for all the baseline vehicle solutions.

The vehicles were solved for payload weights ranging from the baseline 20,000 lb (9070 kg) up to 70,000 lb (31,752 kg) in increments of 10,000 lb. The payload volumes extended from the baseline 2,825 ft^3 (80 m^3) up to 9,888 ft^3 (280 m^3).

This payload range setup results in five additional vehicle solutions besides the closed baseline solution for each configuration to be investigated. If this payload trade included every configuration it would require an additional 90 solution runs. To reduce this workload, only about a third of the vehicle configurations were selected for inclusion in the payload growth study. The vehicles chosen were deemed to be either the most promising or the most representative of their respective configuration categories based on the conclusions of the previous chapters. Four SSTO air-breathers, one TSTO air-breather / rocket combination, and one TSTO rocket were selected for inclusion in this study. The four SSTO air-breathers include HTHL and VTHL configurations for both the inward-turning and 2D inlet types. The HTHL air-breathers are the all-hydrogen vehicles while the VTHL air-breathers are the ones utilizing hydrocarbon fuel for the first trajectory segment. The TSTO rocket is the all-hydrocarbon HCR/HCR vehicle. The TSTO air-breather is the VTHL HCR/IN-RB system.

8.2. Payload Growth Results

8.2.1. Gross Takeoff Weight Comparison

The six vehicles were solved across the described payload range, resulting in an additional five solution points for each vehicle, with the exception of the two horizontal takeoff configurations, which were only run until their gross takeoff weights exceeded the assumed runway bearing load limit of 1.5 million pounds. There is no comparable gross weight limit for the vertically-launched vehicles. Figure 8.1 shows the gross weights of the six solutions for each of the different payload sizes.

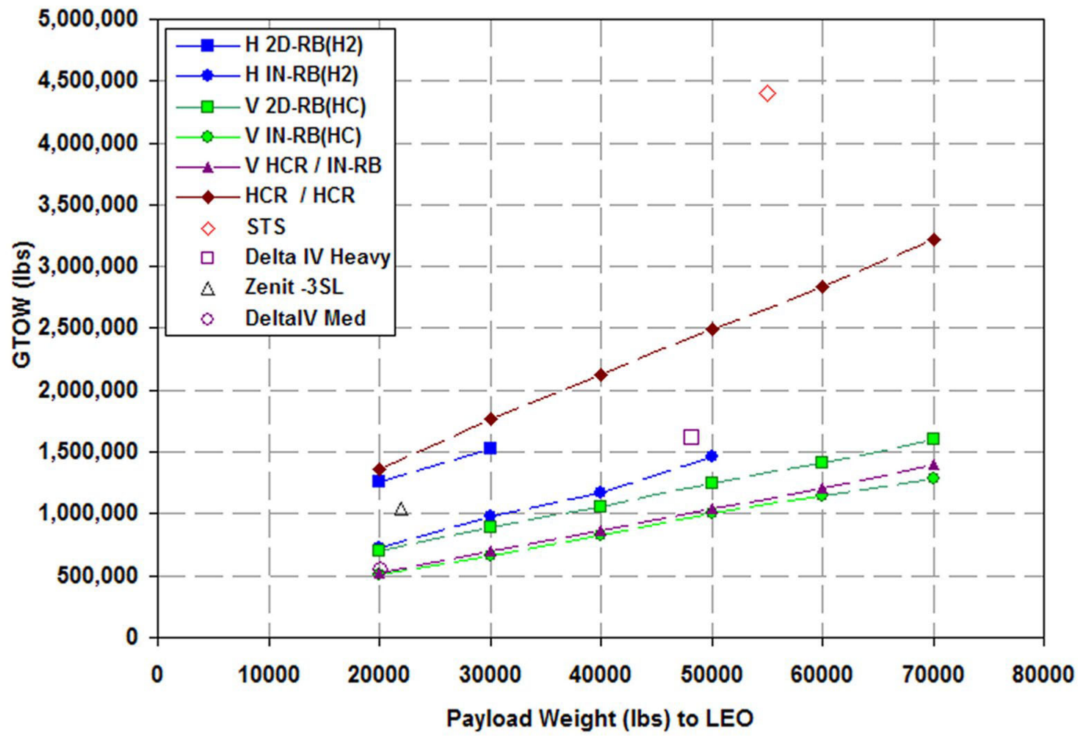


Figure 8.1 Payload Growth: Gross Weight Comparison

Each point on the figure is a completed and "closed" vehicle solution. Also plotted on the figure are the design points for several of the existing expendable launchers as well as the Space Shuttle. As shown, the solution trends for a change in a fixed-weight item such as the payload exhibit a fairly linear response. As expected, the all-rocket HCR/HCR tracks heavier in gross weight than the air-breathing vehicles. However, it has a significantly lower gross weight than the Space Shuttle for the same payload volume and weight. The higher gross weight of the Shuttle is due to its lower performing solid propellant rocket motors versus the all liquid propelled HCR/HCR. The air-breathing vehicles come in with significantly lower gross weights, with the exception of the horizontal 2D SSTO which exceeds the runway bearing load limit almost immediately at 30,000 lb payload. The horizontal inward-turning SSTO can carry a further 20,000 lb before it exceeds the limit at 50,000 lb. The VTHL air-breathers, both the SSTO and TSTO, are even lower in gross weight. These results indicate that there may be a future for vertically-launched air-breathers not only in the small payload class, but also for heavy lift. A SSTO VTHL air-breather could lift the same payload weight and volume as the Space Shuttle at a fourth of the gross weight.

8.2.2. Empty Weight Comparison

The empty weights of the six vehicles for the same payload trade are shown in Figure 8.2 plotted against the empty weights of several existing expendable launchers and the Space Shuttle.

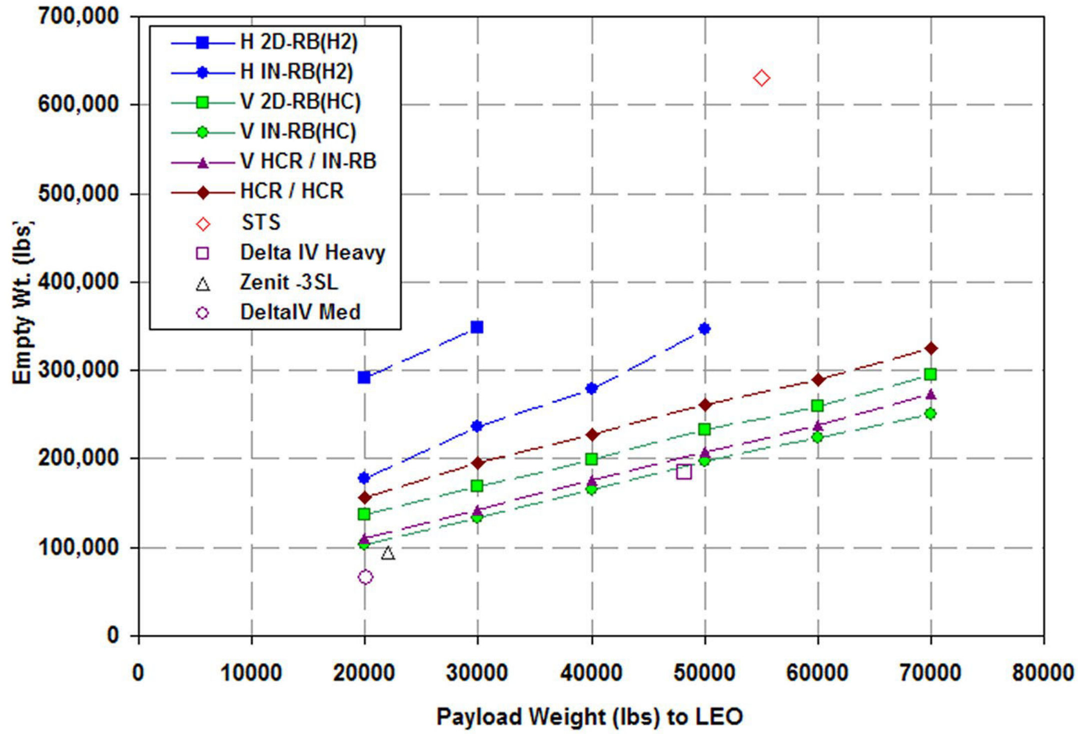


Figure 8.2 Payload Growth: Empty Weight Comparison

The solutions show the same linear response as was observed in the gross weight. The relative placement of all the configurations is also similar with the exception of the TSTO rocket which has an empty weight lower than the SSTO HTHL air-breathers but higher than the VTHL air-breathers. The slopes of the growth responses for the VTHL vehicles, both air-breathers and rockets, remain nearly the same across the payload range. They also track slightly higher than the weights of the expendable vehicles as would be expected. The all-rocket HCR/HCR remains very competitive in empty weight with the air-breathing vehicles at any of the payload sizes and is a definite improvement over the current Space Shuttle.

8.2.3. Wetted Area Comparison

The value of the wetted area as a figure of merit was discussed in Chapter 2. The wetted areas for the payload trade study are presented in Figure 8.3.

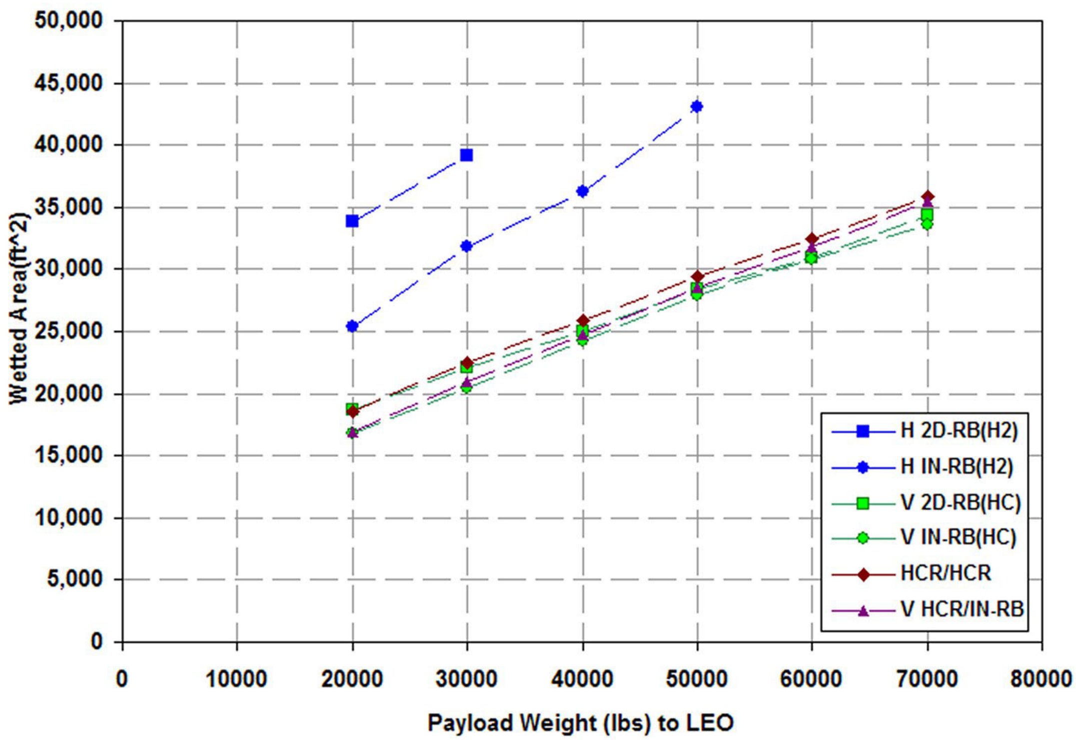


Figure 8.3 Payload Growth: Wetted Area Comparison

The wetted area is primarily used as an indication of the amount of surface area requiring TPS inspection and refurbishment. The trends in wetted area mirror the trends seen previously in empty weight. The VTHL vehicles are very closely grouped with the inward-turning air-breathers in the lowest spot with the TSTO HCR/HCR rocket close by. The outliers are once again the horizontal vehicles.

8.2.4. Maintenance and Refurbishment Comparison

The last figure of merit employed for this study was the estimation each configuration's maintenance and refurbishment cost. The maintenance cost is expressed in terms of required man-hours and is broken down into the maintenance costs for the TPS, engines, and fluid related subsystems for each vehicle and/or stage. Before presenting the variation in maintenance hours for each vehicle across the payload spectrum, it is instructive to view a breakdown of the total maintenance cost into its principal constituents. This is done in Figure 8.4 for the six vehicles at the baseline payload case of 20,000 lb.

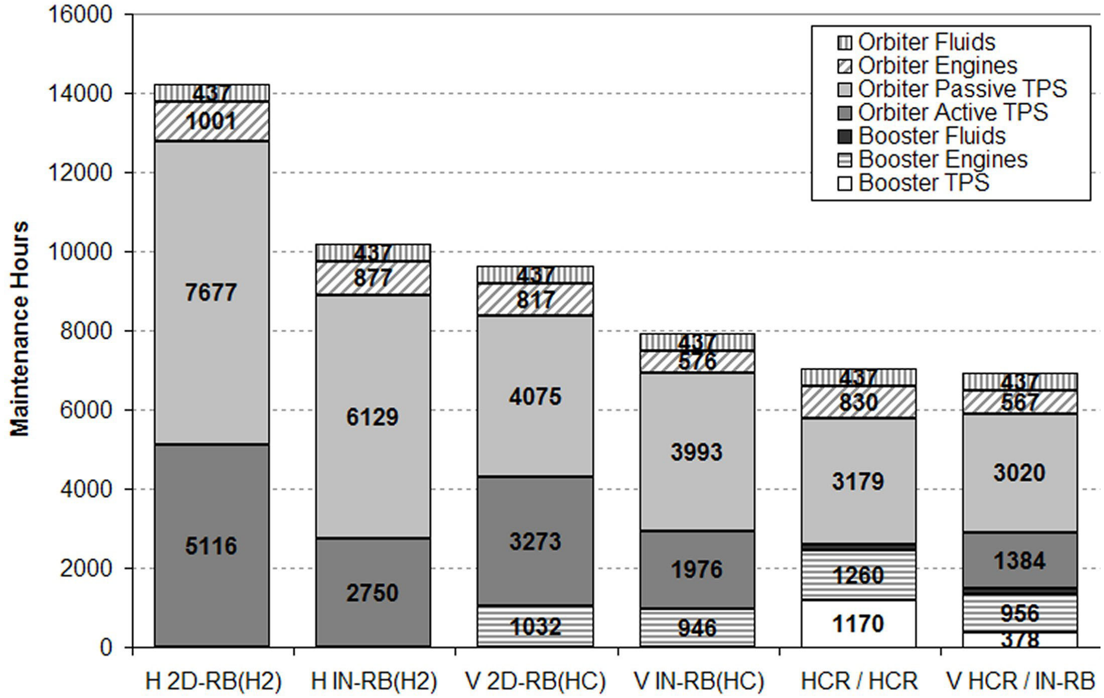


Figure 8.4 Baseline Payload: Maintenance Hours Breakdown and Comparison

For the two TSTO vehicles at the right of the figure, the constituents are divided into the parts corresponding to the orbiter and booster. Maintaining that notation, the SSTO vehicles are listed as orbiter TPS, etc, without an associated booster. In the case of the two SSTO VTHL air-breathers in the middle of the figure, there are two separate rocket engine systems on board; one hydrocarbon system for takeoff, and a hydrogen system for ascent. Both engine sets will need maintained, and are here divided under the names of booster engines and orbiter engines though they are together in the same single vehicle.

The figure shows that the maintenance associated with the active and passive TPS systems is the largest part of the refurbishment cost. This fact is especially true for the SSTO vehicles which carry their whole surface through the entire trajectory. The TSTO HCR/HCR rocket has a high cost for its orbiter TPS, but the booster is much cheaper. The TPS required for the Mach 10 booster is much less capable, and easier to maintain, than the TPS required for the orbiter's re-entry. The TSTO air-breather / rocket combination at the right of the figure benefits from this fact to an even greater extent as its booster only goes to Mach 4. The SSTO VTHL vehicles have much less total maintenance than their HTHL counterparts due to their smaller TPS surface area. However, they do have higher total engine maintenance because of the higher takeoff thrust requirement for a VTHL vehicle versus an HTHL. The values for the fluid system maintenance are based on the number of OMS and RCS thrusters, and APUs that are present and are therefore often the same for the different vehicles. The VTHL inward-turning SSTO and TSTO and the HCR/HCR TSTO rocket have nearly the same total maintenance costs based on the assumptions made.

The total maintenance costs were computed in the same manner for the vehicles across the range of payload solutions as presented in Figure 8.5.

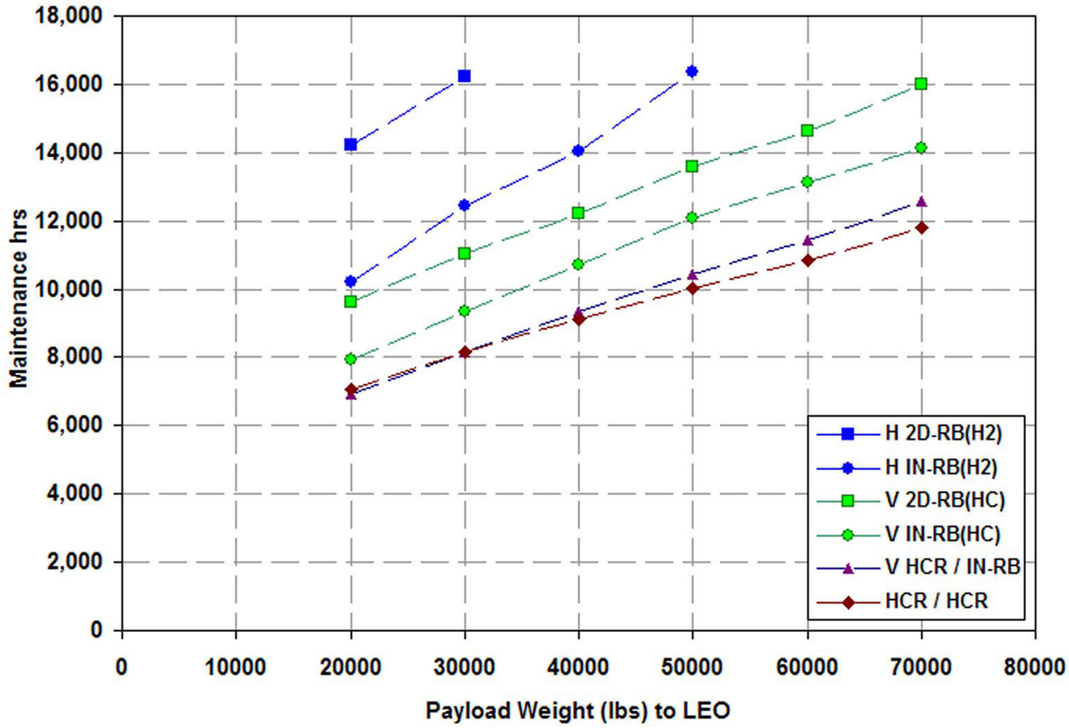


Figure 8.5 Payload Growth: Maintenance Hours Comparison

As seen in the previous figures, there is no payload size at which the trend behavior of the solutions diverges; they remain nearly linear throughout. In terms of refurbishment cost, there is more spread in the data than for the previous metrics. The horizontal vehicles are clearly the most expensive. Since the TPS area and type are the principal cost drivers, it's no surprise to see the larger horizontal vehicles have higher turn-around cost. The same reason applies to the area reduction achieved with the inward-turning inlet which causes it to come in cheaper than the same configuration with a 2D inlet. The lowest maintenance cost is achieved by the two TSTO configurations. The HCR/HCR rocket and HCR/IN-RB air-breather both benefit from boosters that require little TPS cost. This reduction causes them to surpass the SSTO air-breathers in terms of refurbishment. This study did not investigate the operations or integration and assembly[12] cost difference between a two-stage and a single-stage vehicle, but it is entirely possible that the savings in these areas would level the total operation cost between the TSTO HCR/HCR rocket and the SSTO VTHL IN-RB(HC) air-breather.

8.3. *Payload Growth Conclusions*

The results of the payload weight trade study performed in this chapter lead to some straightforward conclusions:

- The large physical size of the horizontal takeoff SSTO air-breathers causes them to have higher maintenance costs than any of the vertical takeoff SSTO or TSTO vehicles. They also have a more limited payload capacity before surpassing the assumed runway bearing load. They have the highest empty weights across the payload range.
- There are no surprising switches in the trends of the vehicles across the different payload cases. Vehicles that seem superior at the baseline

payload remain so at elevated payload sizes in terms of weights and maintenance costs.

- The TSTO all-rocket HCR/HCR configuration has the largest gross weight but the smallest maintenance cost of the vehicles considered.
- The SSTO and TSTO VTHL air-breathers can be competitive with the TSTO all-rocket vehicle in terms of maintenance cost and empty weight. The VTHL air-breathers provide for some interesting possibilities for future heavy lift vehicles.

Chapter 9. Overall Conclusions

This investigation has considered eighteen separate vehicles from several possible configuration possibilities for reusable launch vehicles. The capabilities of a fully-reusable all-rocket two-stage launch vehicle were established in Chapter 4 and used as a baseline vehicle for comparison. The primary emphasis of this work was to determine whether air-breathing launch vehicle configurations could represent an improvement over the baseline vehicle. The air-breathing vehicles considered in Chapter 5 and Chapter 6 included both horizontal and vertical takeoff operational modes for either single- or two-stage configurations and investigated the impact of different inlet geometries and propellant selection. A detailed weight growth investigation was performed in Chapter 7 to discover the scaling behavior of each configuration for increased or decreased structural weight. The understanding of this growth behavior helped to identify configurations that had minimal scaling response to technological uncertainty and consequently exhibited decreased design risk. Chapter 8 investigated the solutions of the most promising vehicles for a wide range of payload weights and determined the vehicles with the lowest maintenance costs. Each of the previous chapters has contained a description of the specific conclusions drawn from the work of that chapter. The overall conclusions for each major configuration category considering all of the investigated criteria as a whole are presented below:

9.1. TSTO Rockets

The fully-reusable TSTO rocket configuration was considered to be the type of reusable launch vehicle that could be constructed in the immediate future with virtually no additional technology development required. Three vehicles were created; differing only by propellant selection. The HR/HR all-hydrogen vehicle had the lightest gross weight but the heaviest empty weight. The best configuration was determined to be the all-hydrocarbon HCR/HCR. As noted in Chapter 7, multi-stage vehicles have fairly low growth factors and this was seen in the growth solutions of the three TSTO rockets. The payload trade study of Chapter 8 showed that, compared to existing launch vehicles, this configuration would represent a great improvement over the partially reusable Shuttle. The TSTO rockets turned out to be a fairly good solution in terms of the applied figures of merit and was a difficult vehicle to surpass due to its light empty weight and simplicity compared to the air-breathers.

9.2. *Horizontal Takeoff SSTO Air-Breathers*

This configuration is the most-widely studied hypersonic SSTO. The vehicle is a single-stage configuration that takes off horizontally, hopefully from a standard runway, under turbine or rocket power until ramjet/scramjet start. After the scramjet cutoff at around Mach 14, integrated rockets boost the vehicle the remainder of the way to orbit. Five vehicles were created with this configuration and differed by inlet type, propellant loading selection, and choice of low-speed propulsion cycle. The drawback of a horizontal takeoff system is that the wings and landing gear are required to support the gross weight of the vehicle. The additional weight of these components proved to be a burden for these vehicles to carry all the way to orbit. The substitution of hydrocarbon fuel in place of hydrogen for the low-speed trajectory segment increased the gross weight, thus exacerbating the situation further. The rocket-powered horizontal SSTO air-breathers were much larger vehicles than their vertical counterparts. The worst performer of the entire study was the horizontal takeoff turbine-powered vehicle. The large weight and poor internal volume usage of the turbines caused this vehicle to close with an empty weight larger than the gross weight of other configurations. The gross weight of the turbine vehicle was right at the assumed maximum runway bearing load of 1.5 million lb. The other horizontal vehicles were lighter, but were as large as the largest existing aircraft. The EISP advantages of the inward-turning inlet helped those configurations to close much smaller than their 2D equivalents. The closing behavior of the horizontal configurations combined with the fact that they were single-stage vehicles caused them to have the largest growth response of any vehicle studied. This is a severe drawback for any vehicle with as much associated technological uncertainty as a single-stage air-breather. The large gross weight of these horizontal systems rendered them unable to withstand much of an increase in payload weight without exceeding the runway limit. The large size and consequently large TPS surface area makes these vehicles very expensive to maintain and time-consuming to turn-around compared to the other vehicles in this study. These results prove definitively that just because a spacecraft may take-off like an airplane does not mean that it will automatically have airplane-like scaling behavior or operations and refurbishment cost.

9.3. Vertical Takeoff SSTO Air-Breathers

This configuration is very similar to the rocket powered vehicles of the horizontal configuration. Four vertical takeoff SSTO vehicles were created; two inward-turing vehicles and two 2D inlet vehicles; one of each was all-hydrogen fueled, and the other investigated the volumetric impacts of replacing the low-speed rocket's hydrogen fuel with hydrocarbon. The rockets for VTHL vehicles were sized for thrust to weight of takeoff of 1.4 and the wings and landing gear are sized for landing the empty weight at the end of the mission. This sizing difference is the major reason that the vertically-launched SSTO air-breathers closed at much smaller sizes than the horizontally-launched versions. The propellant switch was done in an attempt to reduce empty weight, as was witnessed by the hydrocarbon-fueled TSTO rockets. However, the change yielded a decrease in gross and empty weight versus the all-hydrogen versions. This behavior was shown to be a result of decreased drag during the hypersonic trajectory due to the smaller vehicle size of the hydrocarbon versions. The better scaling behavior mitigated the runaway growth behavior seen in the horizontal vehicles, though the vertical air-breathers still have moderate growth factors because they are single-stage configurations. The payload trade showed that it was possible to achieve Space Shuttle class payloads at a quarter of the gross weight with a SSTO VTHL air-breathing launch vehicle. The vertically launched SSTO vehicles had comparable maintenance cost compared to the baseline TSTO rocket. This data in this study identify the vertically launched air-breathing configuration with a hydrocarbon-fueled first trajectory segment of either inlet type as the most promising and possible SSTO vehicles.

9.4. *Horizontal Takeoff TSTO Air-Breathers*

Air-breathing technology was also investigated in two-stage configurations. Two configurations of HTHL TSTO air-breathers were considered. The first horizontally launched TSTO air-breather consisted of an air-breathing first stage combined with an upper-stage reusable rocket. This is among the most widely seen TSTO air-breathing configurations. The air-breathing booster would takeoff horizontally under rocket or turbine power, accelerate to ramjet/scramjet start and then fly up to Mach 10 before staging the rocket orbiter. Three vehicles for this configuration were analyzed each with a different low-speed propulsion type (turbines or rockets) or propellant selection. The second configuration was also horizontally launched, but placed the air-breathing elements as part of the upper-stage. The booster stage for this case was a Mach 4 turbine powered aircraft carry vehicle which would carry the air-breathing orbiter up to ramjet/scramjet start. Only one vehicle was created for this configuration. Both of these horizontal configurations had the same wing and landing gear sizing influences as the

SSTO but it was much less of a problem as these elements were carried by the booster and were only carried as far as staging; naturally it was more of an issue for the Mach 10 air-breathing booster configuration than for the Mach 4 turbine booster. Of the three vehicles with air-breathing boosters, the turbine powered vehicle had the highest empty weight, but the lowest gross weight. For the rocket-powered vehicles, the all-hydrogen fueled vehicle was lighter than the hydrocarbon first segment version. The high staging velocity of all three of these vehicles means that they have traveled a substantial distance down-range from the launch site. Returning the booster to the launch site becomes a major design load on the configuration in terms of flyback fuel and engines. Lighter than all three of these three vehicles in gross weight and equivalent in empty weight and with a greatly reduced fly-back requirement was the second configuration composed of the turbine booster and the upper-stage air-breathing orbiter. The empty weight growth study determined that both of these configurations had roughly the same growth factors as the TSTO rockets but at twice the empty weight. A payload trade was not performed on these configurations. These two configurations both represent more development cost for each of their stages than would be likely for a two-stage rocket and do not appear at all competitive. However, the low growth response of these vehicles was identified as a beneficial attribute that could result in one of these configurations being used as a stepping stone towards achieving an SSTO air-breather. As the upper-stage air-breather has much more in common with an eventual SSTO, it would be the configuration of choice for such a pioneering role. The study identified no advantage in improving space access for the horizontal takeoff TSTO configuration with air-breathing boosters and upper-stage orbiters.

9.5. Vertical Takeoff TSTO Air-Breathers

The last configuration was also a TSTO air-breathing arrangement similar to those of the previous section but with a vertical takeoff rocket booster and an upper-stage air-breathing orbiter. The air-breathing stage of this configuration is identical to the air-breathing stage carried by the horizontal takeoff configuration discussed above. The booster stages at Mach 4. Two vehicles of this configuration were analyzed, one with an inward-turning inlet air-breather and the other with a 2D inlet. These vehicles closed at almost the same weight values as the VTHL SSTO versions of the same. The boosters for this configuration stage at a low enough velocity to glide back to the launch site and have minimal TPS. This configuration exhibits the same low growth factors as the other TSTO vehicles but at a reduced weight compared to the TSTO rockets. The payload trade study showed that this configuration was comparable to a TSTO rocket across the spectrum in terms of maintenance cost and was lower in empty weight and gross weight. This configuration tracks very similarly as the VTHL SSTO configuration, but is obviously a two-stage vehicle. Further studies of integration, operations and procurement cost would be required to choose between the two. This configuration would be the best choice for the development of hypersonic air-breathing technology in a system with lower design risk while still resulting in a vehicle that is functional and competitive with the all-rocket alternative. Experience gained during such a program would likely result in advances that could then be put towards an improved SSTO air-breathing launch vehicle.

9.6. Evolutionary Path of Air-Breathing Technology

Combining the conclusions garnered from the data presented in this work, an evolution of air-breathing technology can be identified. The lessons learned from past SSTO RLV failures should serve as vivid reminders of the results of tackling highly sensitive SSTO systems without a solid grasp of the technology to be utilized. A single-stage air-breathing launch vehicle program must be built on reliable experience with the technology involved if it is to have a high probability of success. Two-stage air-breathing systems provide an environment in which to try out the associated technologies in an operational and capable system which much less design risk. Even so, our actual flight experience with scramjet technology and materials is extremely limited. The identification of the best air-breathing configurations is meaningless if the associated technology cannot be developed. This would suggest that an experimental program should be undertaken with the goal of performing large numbers of flights and answering the fundamental hypersonic questions that represent “make or break” issues for air-breathing launch vehicles. The technology levels assumed for this study show that the VTHL air-breathing configurations could be competitive with the TSTO rockets. Surpassing the rockets would require improving the technologies that are not shared between them such as a significant weight reduction in active cooling TPS and conformal tanks and/or an improvement in the propulsive abilities of the scramjet engine. Many studies before this have identified the possible advantages of an air-breathing launch vehicle, especially if it is single-stage, over current and future expendable and reusable rockets. Having established the potential, it is now time to “answer the fundamental question” as to whether the technology is technologically achievable and economically feasible. Combining all of these considerations and applying the conclusions of this study, a possible evolutionary path is suggested in Figure 9.1.

All the vehicles in this investigation have been fully-reusable launch vehicles. A recently completed study on two-stage rockets has identified a partially-reusable TSTO rocket consisting of a reusable booster and an expendable orbiter that handily outperforms the baseline TSTO rocket in maintenance cost and empty weight. This partially reusable vehicle would likely decrease the competitiveness of reusable air-breathing launchers as applied to current and predicted flight rates. A more detailed programmatic cost study would be revealing.

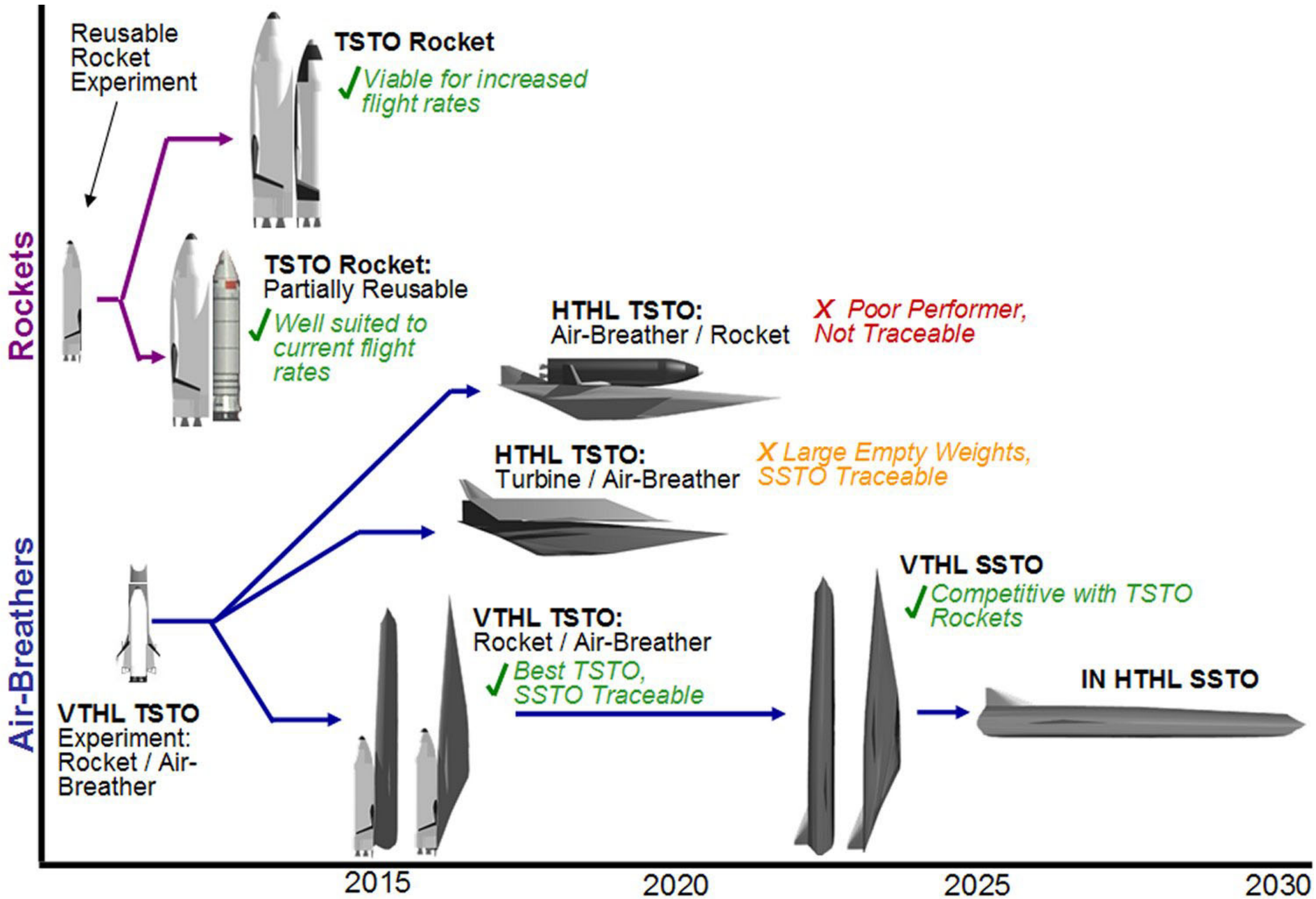
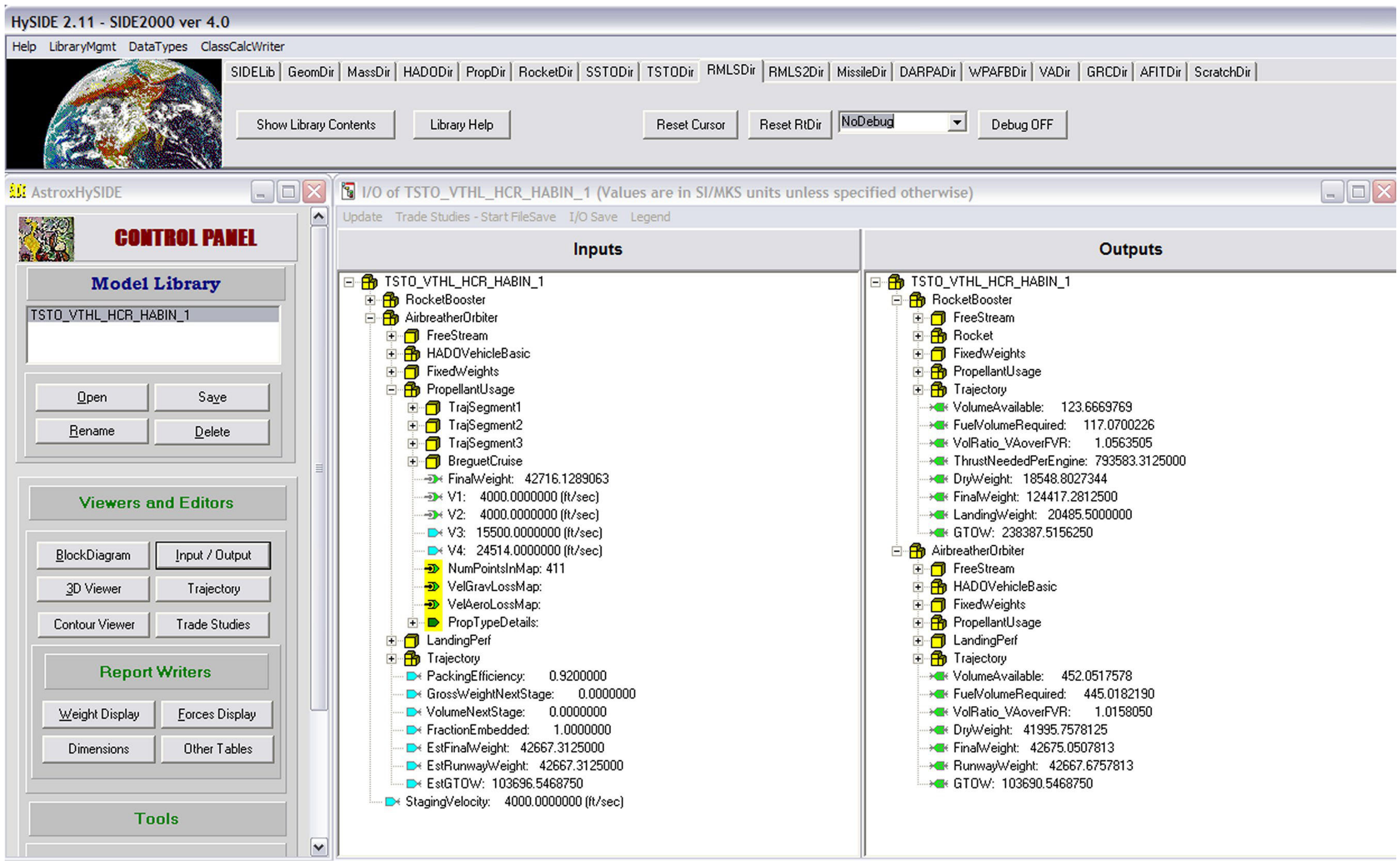


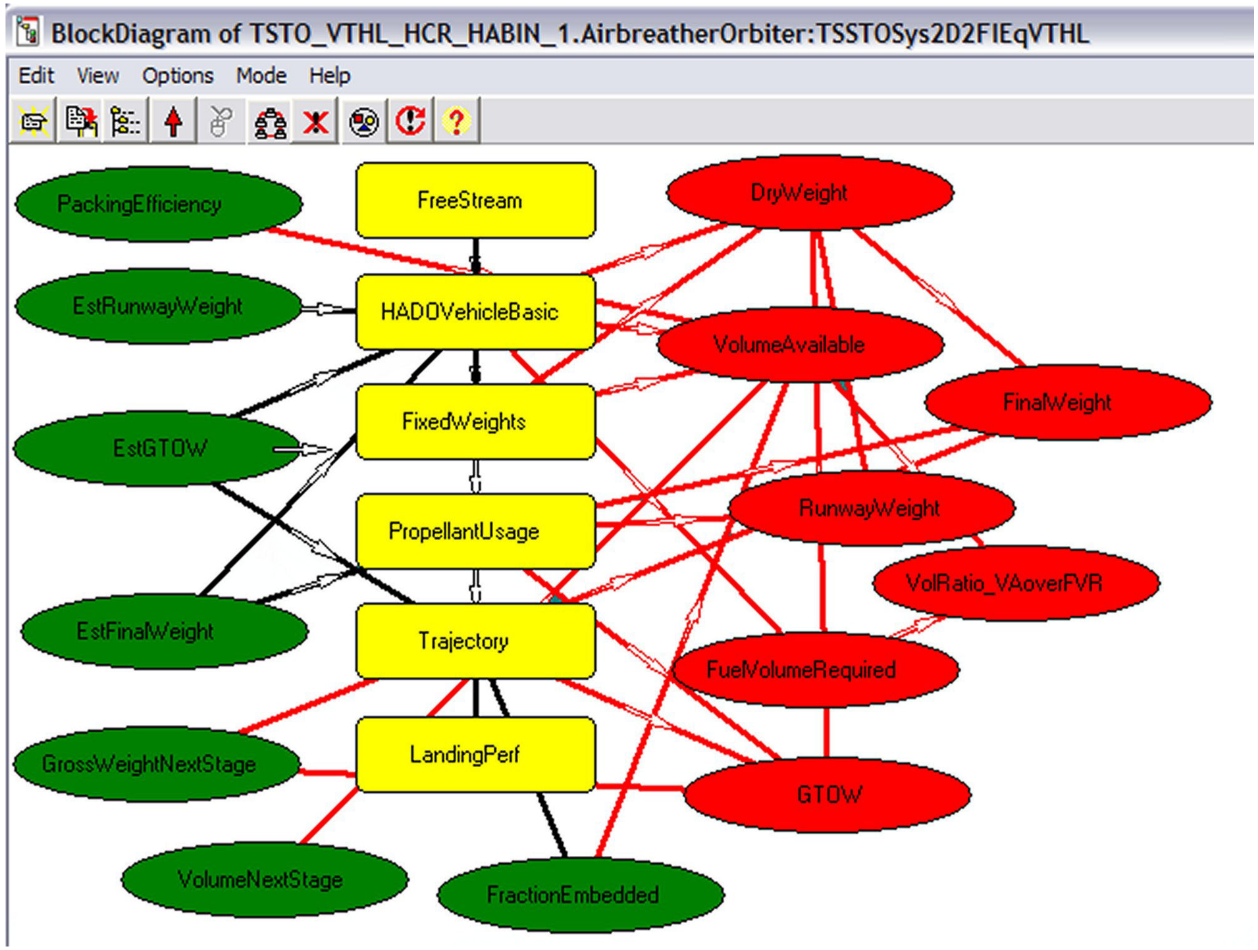
Figure 9.1 Evolutionary Development Path of Air-Breathing Vehicles

Appendix A: HySIDE Design Code

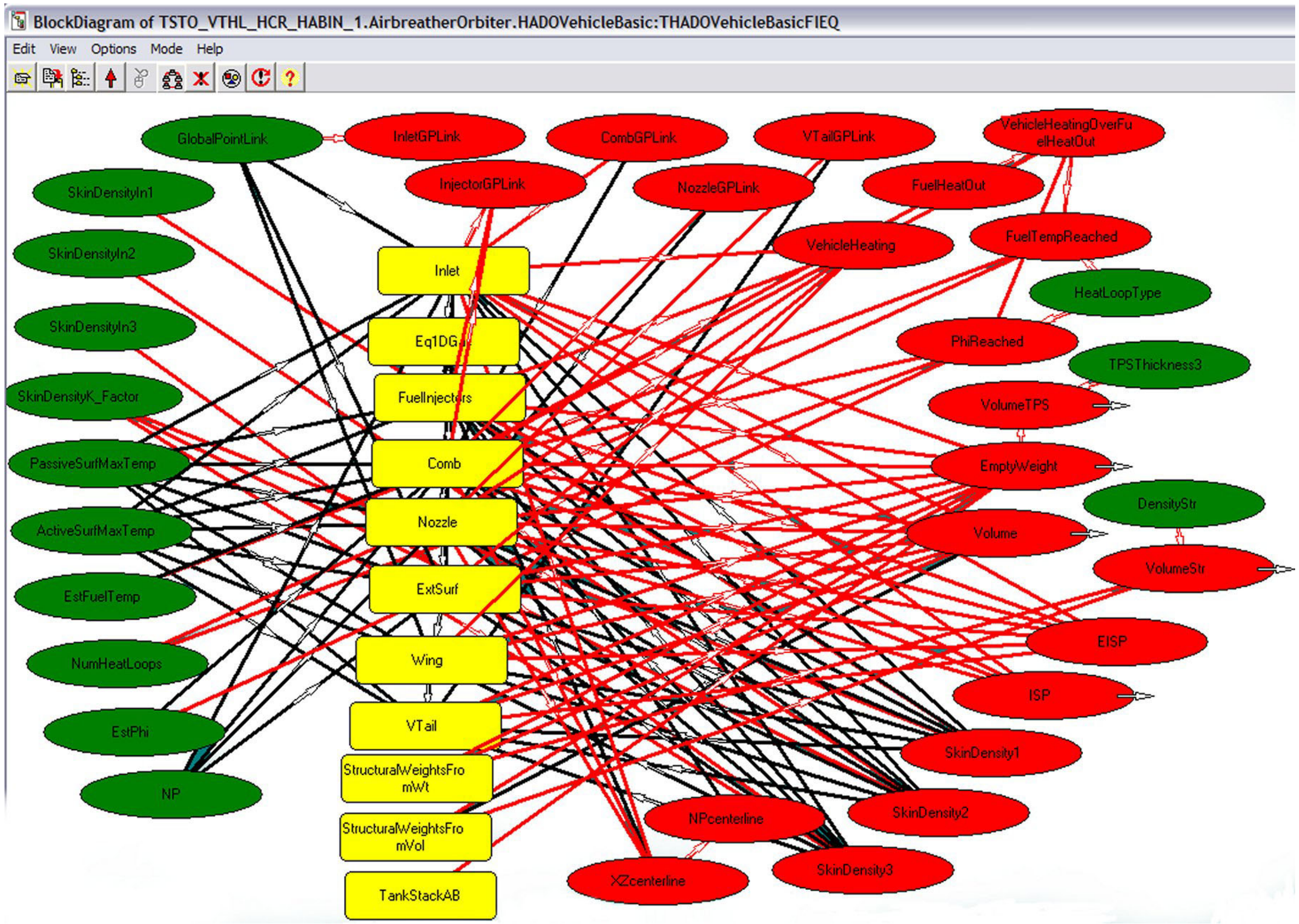
A.1 User Interface and Input/Output Viewer



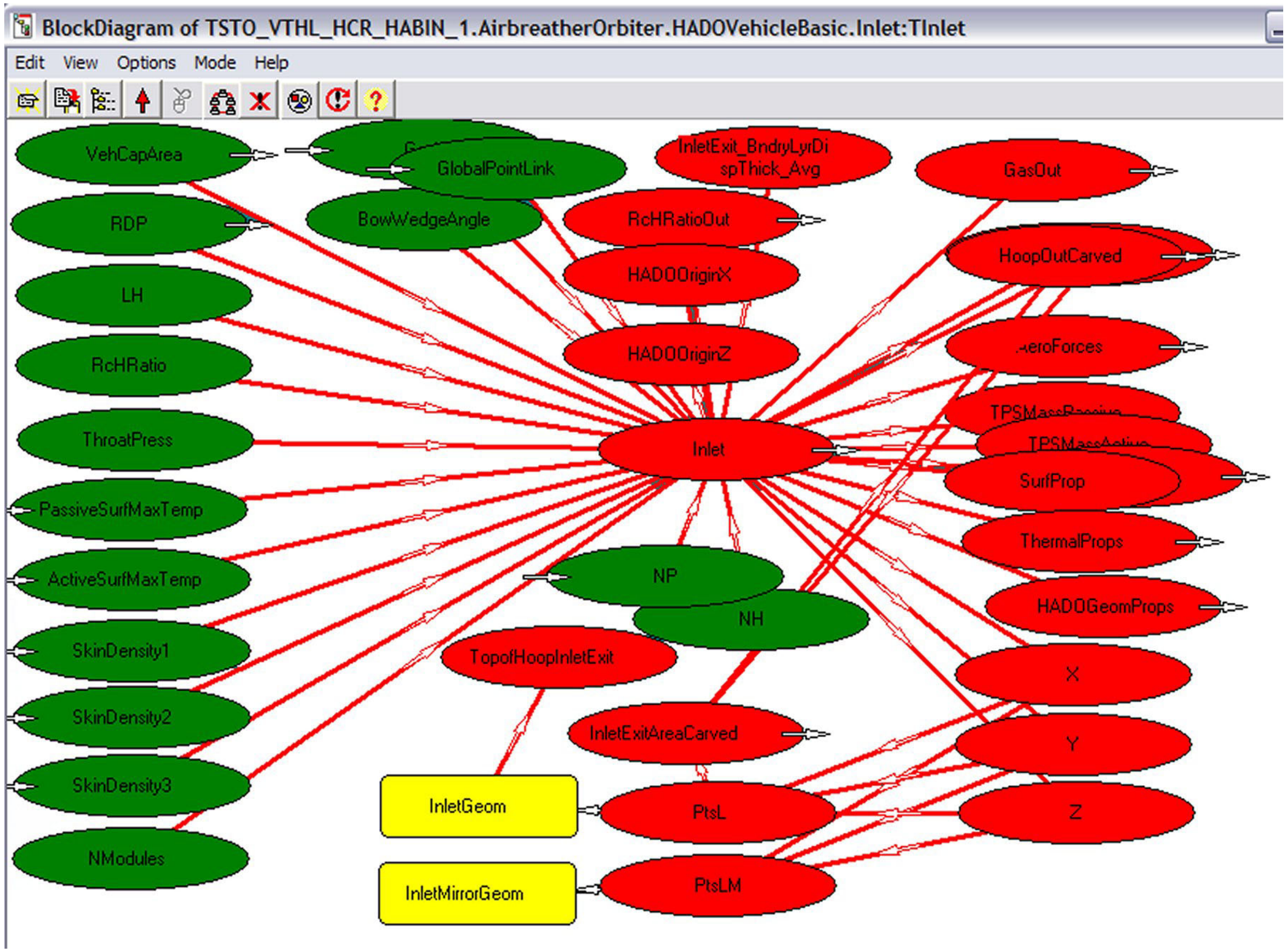
A.2 System Level Hierarchy: Air-Breathing System Model



A.3 Vehicle Level Hierarchy: HADOVehicleBasic Vehicle Model



A.4 Component Level Hierarchy: Inlet Model Components



Appendix B: Vehicle Solution Summaries

B.1 TSTO Rocket Summaries

TSTO ROCKET SUMMARY	HR-HR	HCR-HR	HCR-HCR
Gross Takeoff Weight	1020980	1171500	1419860
Empty Weight	234596	194682	199737
Fixed Weight Total	20000	20000	20000
BOOSTER WEIGHT SUMMARY			
Booster GTOW	705075	855595	1030928
Booster Empty Weight	146576	106663	126390
Wing Total	17581	13012	15588
TPS	4083	3010	3554
Structure	13498	10002	12034
Fuselage Total	6938	4229	4937
Passive TPS	6265	3747	4320
Active TPS	0	0	0
Body Flap Structure	673	482	617
Tank Stack Total	17944	9358	11528
Hydrogen Tank	12234	0	0
RP1 Tank	0	3336	4029
LOX Tank	4581	5588	6710
Inter-Tank Structure	1129	433	789
Thrust Structure / Aft Skirt	9744	3340	4091
Engine Cluster Total	22783	22447	27069
Structural Wt. from Vol.	30415	20402	22828
Structural Wt. from Wt.	41172	32106	38259
Landing Gear	6898	5245	6226
TakeOff Rockets	0	0	0
TakeOff Turbines	0	0	0
Flyback Propulsion	29885	22724	26975
Piggyback Structure	3336	3336	4107
OMS Total	0	0	0
OMS Engines	0	0	0
OMS Fuel	0	0	0
RCS Total	1053	801	950
RCS Engines	681	518	615
RCS Fuel	372	283	335
Propellant Total	558494	748928	904537
Traj Segment 1	558494	748928	904537
Traj Segment 2	0	0	0
Traj Segment 3	0	0	0

TWO-STAGE ROCKETS

ORBITER WEIGHT SUMMARY	HR-HR	HCR-HR	HCR-HCR
Orbiter GTOW (+Payload)	315905	315905	388932
Orbiter Empty Weight	68020	68020	53347
Wing Total	13751	13751	11714
TPS	6389	6389	5356
Structure	7362	7362	6358
Fuselage Total	5278.6	5278.6	3708.3
Passive TPS	4888.3	4888.3	3384.3
Active TPS	0.0	0.0	0.0
Body Flap Structure	390	390	324
Tank Stack Total	7725	7725	4298
Hydrogen Tank	4934	4934	0
RP1 Tank	0	0	1387
LOX Tank	2090	2090	2451
Inter-Tank Structure	701	701	460
Thrust Structure / Aft Skirt	5800	5800	3872
Engine Cluster Total	5091	5091	5369
Structural Wt. from Vol.	20932	20932	16012
Structural Wt. from Wt.	9442	9442	8374
Landing Gear	4072	4072	3476
TakeOff Rockets	0	0	0
TakeOff Turbines	0	0	0
Flyback Propulsion	0	0	0
Piggyback Structure	834	834	1027
OMS Total	2628	2628	2243
OMS Engines	261	261	223
OMS Fuel	2367	2367	2020
RCS Total	1908	1908	1628
RCS Engines	402	402	343
RCS Fuel	1506	1506	1285
Propellant Total	227878	227878	315582
Traj Segment 1	0	0	0
Traj Segment 2	0	0	0
Traj Segment 3	227878	227878	315582

B.2 SSTO Air-Breather Summaries

SSTO AIR-BREATHER SUMMARY	IN-RB(H2) VTHL	IN-RB(HC) VTHL	2D-RB(H2) VTHL	2D-RB(HC) VTHL	IN-RB(H2) HTHL	IN-RB(HC) HTHL	2D-RB(H2) HTHL	2D-RB(HC) HTHL	2D-TB(HC) HTHL
Gross Takeoff Weight	**574272**	**502816**	**816776**	**702916**	**724934**	**817393**	**1255020**	**1418680**	**1730240**
Empty Weight	**142576**	**109311**	**190720**	**144415**	**186301**	**188020**	**305244**	**308294**	**545539**
Fixed Weight Total	**20000**	**20000**	**20000**	**20000**	**20000**	**20000**	**20000**	**20000**	**20000**
Wing Total	**6107**	**4882**	**9639**	**7563**	**14013**	**17137**	**30653**	**37236**	**36275**
TPS	2014	1610	3176	2492	4615	5644	10091	12257	11946
Structure	4093	3272	6462	5071	9397	11494	20562	24979	24329
Tail Total	**1705**	**1337**	**2278**	**1746**	**2843**	**3249**	**5264**	**6052**	**7598**
TPS	461	368	600	471	733	826	1269	1434	1749
Structure	1245	969	1679	1276	2110	2423	3995	4618	5849
Fuselage TPS Total	**43149**	**34896**	**54105**	**43871**	**49370**	**47433**	**69268**	**65553**	**98651**
Passive TPS	27677	22278	27226	21793	31885	30545	35273	33439	48402
Active TPS	15472	12618	26880	22078	17485	16888	33995	32114	50249
Tank Stack Total	**30708**	**21448**	**42520**	**29089**	**39103**	**35898**	**65514**	**59998**	**87592**
Hydrogen Tank	27750		38029	24243	35471	30632	58764	50372	78862
RP1 Tank	0	800	0	1125	0	1267	0	2228	1919
LOX Tank	2958	2503	4492	3720	3632	3998	6750	7398	6810
Structural Wt. from Vol.	**33161**	**24121**	**44597**	**32015**	**41382**	**39241**	**67560**	**62837**	**90735**
Structural Wt. from Wt.	**27746**	**22627**	**37581**	**30131**	**39590**	**45061**	**66986**	**76618**	**224689**
Landing Gear	7384	5903	9618	7547	21531	24277	37275	42135	51387
TakeOff Rockets	12032	10066	17113	14072	7595	10070	13148	17478	0
TakeOff Turbines	0	0	0	0	0	0	0	0	144512
OMS Total	**4826**	**3858**	**6286**	**4932**	**6064**	**6208**	**9597**	**9853**	**16681**
OMS Engines	480	384	625	491	603	617	954	980	1659
OMS Fuel	4346	3474	5661	4442	5460	5590	8643	8873	15022
RCS Total	**3503**	**2800**	**4563**	**3580**	**4401**	**4506**	**6966**	**7151**	**12108**
RCS Engines	738	590	962	755	928	950	1468	1508	2552
RCS Fuel	2765	2210	3601	2825	3473	3556	5498	5644	9556
Propellant Total	**411696**	**373505**	**606054**	**538501**	**518632**	**609373**	**929780**	**1090373**	**1164753**
Traj Segment 1	166457	176665	238438	248500	205888	285448	363074	502054	124926
Traj Segment 2	85411	68794	109867	87313	111619	117546	172906	183802	268917
Traj Segment 3	159828	128046	257750	202687	201124	206379	393800	404517	770910

B.3 TSTO Horizontal Air-Breather Summaries

HORIZONTAL TAKEOFF
TWO-STAGE AIR-BREATHERS

TSTO AIR-BREATHER SUMMARY	2D-RB(H2) / HR	2D-RB(HC) / HR	2D-TB(HC) / HR
Gross Takeoff Weight	1033590	1146410	836365
Empty Weight	284324	283994	320000
Fixed Weight Total	20000	20000	20000
AIR-BREATHER BOOSTER WEIGHT SUMMARY			
AB Booster GTOW	795321	908141	598096
AB Booster Empty Weight	226201	225871	261877
Wing Total	55252	65525	33316
TPS	9569	11347	5774
Structure	45682	54177	27542
Tail Total	4226	4750	3333
TPS	1045	1159	845
Structure	3181	3592	2488
Fuselage TPS Total	43708	38602	49119
Passive TPS	21669	19051	22945
Active TPS	22039	19551	26174
Tank Stack Total	30453	24908	19206
Hydrogen Tank	27590	19865	19206
RP1 Tank	0	1870	0
LOX Tank	2864	3174	0
Structural Wt. from Vol.	32060	27066	22447
Structural Wt. from Wt.	62017	66535	135069
Landing Gear	30698	34048	24840
TakeOff Rockets	10612	11770	0
TakeOff Turbines	0	0	102281
Flyback Turbines	13149	13156	0
OMS Total	0	0	0
OMS Engines	0	0	0
OMS Fuel	0	0	0
RCS Total	4292	4294	4623
RCS Engines	2777	2779	2992
RCS Fuel	1515	1515	1632
Propellant Total	567606	680758	334584
Traj Segment 1	318242	421622	66114
Traj Segment 2	86190	95881	92700
Traj Segment 3	0	0	0
Flyback Propellant	163174	163255	175771

ROCKET ORBITER WEIGHT SUMMARY			
Orbiter GTOW (+Payload)	238269	238269	238269
Orbiter Empty Weight	58123	58123	58123
Wing Total	12350	12350	12350
TPS	6244	6244	6244
Structure	6106	6106	6106
Fuselage Total	8347.3	8347	8347.3
Passive TPS	8109	8109	8109
Active TPS	0	0	0
Body Flap Structure	238	238	238
Tank Stack Total	5186	5186	5186
Hydrogen Tank	3393	3393	3393
RP1 Tank	0	0	0
LOX Tank	1257	1257	1257
Inter-Tank Structure	536	536	536
Thrust Structure / Aft Skirt	4452	4452	4452
Engine Cluster Total	3865	3865	3865
Structural Wt. from Vol.	18941	18941	18941
Structural Wt. from Wt.	8540	8540	8540
Landing Gear	3742	3742	3742
TakeOff Rockets	0	0	0
TakeOff Turbines	0	0	0
Flyback Propulsion	0	0	0
Piggyback Structure	629	629	629
OMS Total	2415	2415	2415
OMS Engines	240	240	240
OMS Fuel	2175	2175	2175
RCS Total	1753	1753	1753
RCS Engines	370	370	370
RCS Fuel	1384	1384	1384
Propellant Total	156587	156587	156587
Traj Segment 1	0	0	0
Traj Segment 2	0	0	0
Traj Segment 3	156587	156587	156587

B.4 TSTO Vertical Air-Breather Summaries

VERTICAL TAKEOFF
TWO-STAGE AIR-BREATHERS

TSTO AIR-BREATHER SUMMARY	HCR / IN-RB(H2)	HCR / 2D-RB(H2)
Gross Takeoff Weight	**524916**	**718811**
Empty Weight	**109984**	**146554**
Fixed Weight Total	**20000**	**20000**
AIR-BREATHER ORBITER WEIGHT SUMMARY		
AB Orbiter GTOW	228632	324960
AB Orbiter Empty Weight	68536	94491
Wing Total	4487	7057
TPS	1129	1774
Structure	3358	5283
Tail Total	912	1207
TPS	258	335
Structure	654	872
Fuselage TPS Total	**24376**	**33267**
Passive TPS	16239	16263
Active TPS	8137	17004
Tank Stack Total	**13098**	**18321**
Hydrogen Tank	12306	17050
RP1 Tank	0	0
LOX Tank	793	1271
Structural Wt. from Vol.	**15445**	**20713**
Structural Wt. from Wt.	**14203**	**19098**
Landing Gear	4139	5372
TakeOff Rockets	4790	6809
TakeOff Turbines	0	0
Flyback Turbines	0	0
OMS Total	**2705**	**3511**
OMS Engines	269	349
OMS Fuel	2436	3162
RCS Total	**1964**	**2548**
RCS Engines	414	537
RCS Fuel	1550	2011
Propellant Total	**136110**	**205297**
Traj Segment 1	0	0
Traj Segment 2	46394	61447
Traj Segment 3	89716	143850
Flyback Propellant	0	0

ROCKET BOOSTER WEIGHT SUMMARY		
Booster GTOW (+Payload)	296284	393851
Booster Empty Weight	41449	52063
Wing Total	5147	6133
TPS	1698	2033
Structure	3449	4100
Fuselage Total	4207.6	5099.2
Passive TPS	3971	4794
Active TPS	0	0
Body Flap Structure	237	305
Tank Stack Total	**3417**	**4541**
Hydrogen Tank	0	0
RP1 Tank	1148	1541
LOX Tank	1918	2574
Inter-Tank Structure	351	426
Thrust Structure / Aft Skirt	3109	3794
Engine Cluster Total	10159	13854
Structural Wt. from Vol.	**12329**	**14253**
Structural Wt. from Wt.	**4742**	**6371**
Landing Gear	2019	2551
TakeOff Rockets	0	0
TakeOff Turbines	0	0
Flyback Propulsion	0	0
Piggyback Structure	2414	3432
OMS Total	**0**	**0**
OMS Engines	0	0
OMS Fuel	0	0
RCS Total	**308**	**389**
RCS Engines	199	252
RCS Fuel	109	137
Propellant Total	**254726**	**341667**
Traj Segment 1	254726	341667
Traj Segment 2	0	0
Traj Segment 3	0	0

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