

Comparison of Return to Launch Site Options for a Reusable Booster Stage

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ABSTRACT

There is a major need in the U.S. Air Force to develop launch vehicles that can be used for Operational Responsive Spacelift and possibly be used for rapid global Strike. One strategy to achieve these mission goals is to develop a Reusable Military Launch System (RMLS) or a hybrid system which uses a reusable booster with expendable upper stages. In support of the development work of the Aerospace Systems Design Branch (ASC/ENMD) of the USAF Aeronautical Systems Center at Wright-Patterson AFB, this study looked at comparing three basic methods for Return to Launch Site (RTLS) for a reusable booster. These methods are glideback to launch site, flyback using an airbreathing turbofan, and boostback using the booster's main or secondary rocket engines. The booster carries the upper stage(s) on its back to the staging point. Currently, most RTLS vehicle studies either assume a glideback or flyback booster. Very little work outside of the Kistler K-1 has been done to look at boostback methods. The vehicle modeling was integrated into ModelCenter using the MDO method of Optimizer Based Decomposition to handle the branching trajectory problem that arises from the booster performing a RTLS maneuver. Each of the three vehicles was optimized to minimize dry weight and gross weight separately in order to get a better understanding if boostback can provide any advantages over the two more traditional RTLS methods.

Nomenclature

APAS	Aerodynamic Preliminary Analysis Software	LOX	Liquid Oxygen
BPR	Bypass Ratio	MDO	Multi-Disciplinary Design Optimization
CAD	Computer-Aided Drawing	MER	Mass Estimating Relationship
DOE	Design of Experiments	MR	Mass Ratio
DOF	Degree of Freedom	OBD	Optimizer Based Decomposition
DSM	Design Structure Matrix	POST	Program to Optimize Simulated Trajectories
ΔV	Change in Velocity	RLV	Reusable Launch Vehicle
ELV	Expendable Launch Vehicle	RP	Rocket Grade Kerosene
FPA	Flight Path Angle	RSE	Response Surface Equation
FPI	Fixed Point Iteration	RTLS	Return to Launch Site
GUI	Graphical User Interface	SESAW	Simple Electrical Systems and Avionics Wizard
HABP	Hypersonic Arbitrary Body Program	SSTO	Single Stage To Orbit
ISP	Specific Impulse	TSTO	Two Stage To Orbit
KSC	Kennedy Space Center	UDP	Unified Distributed Panel
LH2	Liquid Hydrogen	USAF	United States Air Force

1.0 Introduction

Ever since the United States became involved in developing launch vehicles, there has been a desired to develop a vehicle that could place an payload in orbit, return to its launch site, and be reused quickly similar to a conventional airplane. The major deterrent to developing a RLV has been the large upfront development cost without the launch frequency necessary to justify that cost. The only partially reusable vehicle developed is the Space Shuttle which has shown to have large operation expenses and a long turn around time. Its solid rocket boosters must be extracted from the ocean and undergo long maintenance procedures to clean out the salt water.

All unmanned launches around the world currently make use of completely expendable launch vehicles which can run up to \$500 million a launch. Along with the current need in the USAF for responsive space lift and for long range strike and the growing space tourist market, there is now a growing desire to develop a partial or totally reusable TSTO launch vehicle to replace the current ELV's and the Shuttle.

A current trend in RLV development is to focus on reusing the booster while leaving the upper stage expendable. A vehicle like this can serve as a stepping stone to a totally reusable system by developing operational techniques, prove technologies, better determine economic benefits, and build public support for reusable launch architectures.

One of the main design decisions for a reusable booster is to determine the method it will use for RTLS. If the booster is unpowered after staging, then there is a limit as to how high the staging can occur so the booster will have enough margin to return and land safely. If the booster uses airbreathing engines, hardware for those engines needs to be added along with another fuel tank thereby increasing the complexity, mass, and cost of the booster. The airbreathing engines, however, will allow for a higher staging point, since it can return after turning around at a point farther downrange. Another possibility for a RTLS booster is to use the ascent rocket engines to provide the necessary acceleration for RTLS.

This study will compare the RTLS methods of boostback, flyback with an airbreathing engine (referred to as "flyback" in this study), and glideback and compare them based on the optimal staging point for both gross mass and dry mass. In order to find this, a multi-disciplinary model of the vehicles incorporating

many different design tools was made to be able to find an optimal sized vehicle based on the staging point while keeping most other parameters constant.

2.0 Historical Background and Previous Work

2.1 Early Historical Look at Reusable Boosters

The desire to build a RLV has been around since the days of the space race to the moon. As with today, they were concerned with the cost of space access. It was believed that economics would limit space exploration and not technology¹. Many early studies focused on reusing the booster as the first method to lower the direct operating costs of placing a payload in orbit.

A study by Boeing² initially looked at the options of a RTLS booster and a booster that flies ballistically into the ocean and is then picked up by a boat. The biggest difference in development cost was the lifting surfaces and the associated modifications to a standard expendable booster, which would increase with staging altitude and Mach number. Also, adding wings would require flight testing for a manned system. Recovering the booster in the ocean, however, would need small modifications adding aerodynamic stabilization and deceleration devices such as parachutes. Overall, a higher research and development cost of almost 30 to 1 to build a RTLS booster gave a much more favorable outlook towards water recovery. The manufacturing cost to build each RTLS booster would cost about 3.5 times that of the ocean recovery. The advantages of the RTLS booster show up when looking at the recurring costs. It was estimated that an individual RTLS booster could be used almost 5-6 times more than the ocean recovery.

2.2 Previous RTLS Comparison Studie

There are no widely known publicly published comparisons in which the boostback RTLS method is compared to other the other methods. The current comparison studies only focus on glideback vs. flyback.

One study conducted at Adelaide University in Australia and the University of Stuttgart looked at glideback and flyback launching out of the Woomera launch site in Australia⁴. In this study both stages were assumed to be reusable with both stages using LOX/RP propellants. Along with analyzing the RTLS methods, the study also noted that it is not optimal to perform high g-loading turns as the extra wing weight would not make up for additional payload. This study allowed for 3.6 g turns during the RTLS branch. The optimal staging point for glideback was at a velocity of about 3937 ft/sec at and altitude of about 16.2 nmi, while flyback staged at about 10,498 ft/sec at an altitude of about 34.5 nmi.

This study did not fix a payload but fixed a gross weight at liftoff. So mass differences between the two RTLS methods must focus on the payload. The flyback vehicle was shown to lift almost 50% more payload into LEO than glideback. Although adding extra engines for flyback, this study recommends using that method as it can lift significantly more payload to orbit.

Another comparison study conducted at Tokyo University compared flyback vs. glideback and also looked at the difference between different fuels, methane, LH2, RP, and densified LH2⁵. This study shows that in order for glideback to be able to occur, the mass ratio between the booster and the orbiter must be small. This study showed for the LOX/RP flyback booster, the dry weight is 17% less than LOX/LH2 but the gross mass is 48% higher. The LOX/Methane booster was heavier in both gross and dry mass than the other propellants. The only glideback boosters looked at in this study were LOX/LH2 showing that glideback had 92% more gross mass and 63% more dry mass, over flyback with LOX/LH2.

2.3 Glideback Example

Although studies have shown that the powered flyback RTLS method can be advantageous when considering the gross and dry weight, glideback can make the booster a simpler vehicle without needing to add in extra hardware for the turbine engine and extra fuel tank. Even going back to the early days of

spaceflight as shown above, there were many ideas to implement the simplicity of gliding back to the launch site after releasing an upper stage(s).

One example of fully reusable TSTO concept conceived at NASA Langley was the Future Space Transportation System to replace the Space Shuttle^{6,7,8}. This system was design to carry 150,000 lbs to LEO. The booster uses LOX/RP propellants and the upper stage uses LOX/LH2 propellants. Since the both stages burn simultaneously, the booster carries extra LH2 in a separate tank for the upper stage. The booster would glideback after staging at Mach 3. The overall payload fraction estimated for this design is about 3%. The total dry weight is estimated to be about 456,000 pounds which is just over 3 times the weight of the payload. The wings were designed for a 2.5g normal acceleration limit. Due to the low staging Mach number, no TPS is required.

2.4 Flyback Example

A major effort since the space shuttle began operating looked at replacing the solid rocket boosters with liquid flyback boosters. The configurations of dual boosters and catamaran booster are shown in Figure 1. The boosters would stage at about Mach 5.2 and an altitude of about 163,000 ft⁹. The boosters would coast to an apogee of about 270,000 ft, re-enter, perform a transonic turn and cruise back to KSC at about 18,500 ft and Mach 0.48. It was estimated that about 20,000 lb of fuel would be needed for the turbine engine¹⁰.

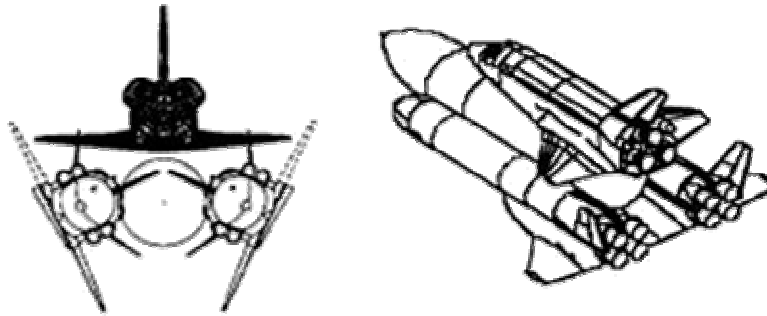


Figure 1. Liquid Flyback Booster Configurations for the Space Shuttle⁹.

2.5 Boostback Example

An example of boostback in which hardware has been built but not yet flown is the Kistler K-1^{13,14,15,16}. This is a fully reusable launch vehicle in which the booster executes a burn similar to the tossback method discussed above, shown in Figure 2. This staging occurs at about Mach 4.4, around 135,000 – 140,000 ft., and 135 seconds into the flight. For the boostback burn, the center engine (out of 3) burns for 35 seconds. The booster uses parachutes to slowdown after re-entry and air bags for landing. The landing takes place at about 12 minutes after liftoff.

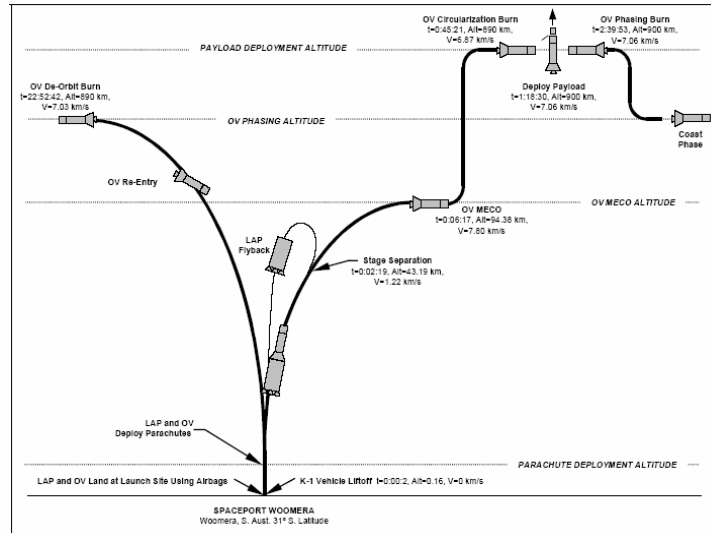


Figure 2. Ascent and Boostback Trajectory for Kistler K-1¹³.

3.0 Technical Approach

The main focus of this study is to compare the vehicle sizes required to complete a certain mission utilizing three different RTLS methods. The vehicles will be compared by the total amount of gross weight and dry weight. The mission requirements for this comparison are to launch a 15,000 lb payload to a 100 nmi circular orbit and a 28.5° inclination. The launch site is Kennedy Space Center (28.5°N latitude and 80.5°W longitude). To ensure enough margin to land back at the launch site, the booster must return to KSC with at least an altitude 15,000 ft. Both stages use LOX/RP-1 for propellant.

3.1 Branching Trajectory Problem

The use of a reusable booster poses a multi-disciplinary problem known as a branching trajectory¹⁷. For a TSTO vehicle, the overall flight path of both stages is broken up into three different branches. The ascent branch includes both stages mated together starting at the launch site and flying to a certain staging point. This staging point is selected based on a certain amount of ideal ΔV from the conditions at the launch site. The upper stage then flies along the orbital branch to orbit insertion. Figure 3 shows a notional branching trajectory. In this study, both the ascent and orbital branch were modeled in the same trajectory input file. The booster executes necessary maneuvers for the RTLS branch from the conditions at staging. A seven parameter state vector is used to identify the staging conditions: latitude, longitude, velocity, flight path angle, altitude, azimuth direction of the velocity vector, and the after staging weight of the booster.

The RTLS branch brings in a modeling problem of the booster when it requires additional propellant. The booster and upper stage without RTLS can easily be sized so the proper payload can be inserted into a desired orbit. Adding in extra propellant for the booster for RTLS, requires the booster to grow in size, thereby increasing the amount propellant needed to reach staging, and the problem becomes cyclical. Feedback is thus required in the vehicle model to ensure proper sizing. In order to model the TSTO vehicle with a reusable booster, MDO methods are needed to handle the feedback aspect of the problem.

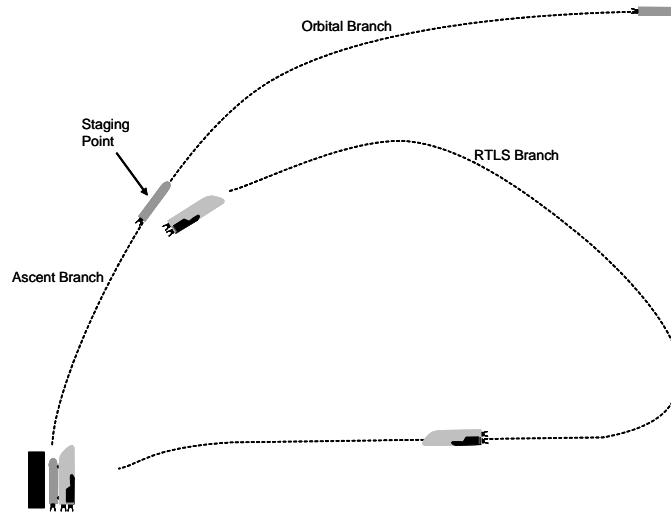


Figure 3. Notional Branching Trajectory.

3.2 Contributing Analyses

Modeling the TSTO vehicle with and RTLS booster is broken down into many different design disciplines that rely on information from other disciplines and assumptions to be made. This section describes each of the different disciplines or contributing analyses, what assumptions are made and what design tool is used.

3.2.1 Configuration

The shape of the booster is based off the shape of the SSTO RLV using the ACRE-92 designed for the NASA HRST study and further modeled by Spaceworks Engineering, Inc.¹⁸. The baseline booster fuselage for this study is cylindrical with a drooped nose section and a blunt end. The propellant tanks make up most of the fuselage with the forward dome of the fuel tank located inside the nose section. There is a 2 foot spacing between the propellant tanks and a 5 foot section in the rear. For the airbreathing RTLS booster, the rear section is assumed to be 10 feet to allow for a flyback fuel tank and extra hardware for the turbine engines, thereby lowering the packaging efficiency. The wing is a delta shape with vertical fins located at the wing tips. The rear of the booster has a body flap underneath the engines.

The upper stage is cylindrical body mounted on top of the booster. The diameter of the upper stage is set to 6 ft. The propellant tanks have domes with a 0.707 height to radius ratio and a 2 foot intertank adapter. The thrust structure is located on the rear dome of the oxidizer tank. The fairing has a 10 foot conical section on top of a cylindrical housing for the payload. A 2-D 3-View of the booster is shown in Figure 4. The baseline configuration parameters are listed in Table I.

Table I. Baseline Configuration Parameters for RTLS Booster.

Fuselage Length	165 ft	Total Verticals Planform Area	425 ft ²
Total Fuselage Volume	94,676 ft ³	Body Flap Length	10 ft
Packaging Efficiency (Glideback and Boostback)	79.55 %	Primary Structure Area	2758 ft ²
Packaging Efficiency (Flyback)	74.55 %	Secondary Structure Area	615.8 ft ²
Structural Span	110 ft	Body Flap Planform Area	280 ft ²
Wing Reference Area	6,000 ft ²	TPS Planform Area	9,512.7 ft ²
Maximum Wing Root Thickness	9 ft	TPS Total Wetted Area	23,579 ft ²

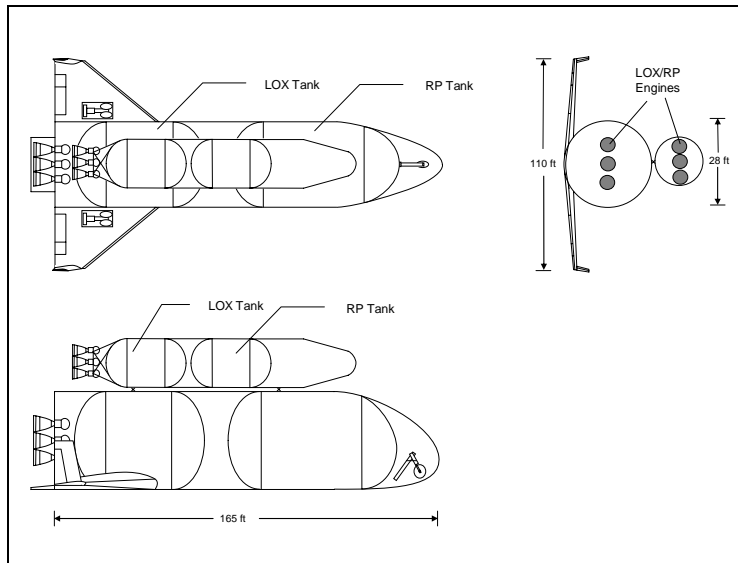


Figure 4. Notional 3-View of Baseline Configuration.

3.2.2 Aerodynamics

The aerodynamic model for the booster was calculated using the APAS code¹⁹. The vehicle inputted into the code had dimensions based on a 0.5 scale factor of the baseline configuration dimensions for the booster shown above. The upper stage was inputted with a 6 ft radius and 40 ft length. The vehicle shape was analyzed in UDP for low speed and transonic flight (Mach 0 – Mach 2) and HABP for the hypersonic flight (Mach 3+).

3.2.3 Rocket Propulsion

Two different rubberized engine types were assumed for the booster and upper stage. Both engines types are single chamber, LOX/RP, gas-generator cycle, with a series flow sequence. The basic engine parameters, listed in Table II, were assumed to be constant for both stages. Each engine has Engine Health Monitoring, double controller redundancy, gimbals, and no engine nacelle.

Table II. Rocket Engine Parameter Held Constant in this Study.

Oxidizer to Fuel Ratio	2.7
Booster Engine Expansion Ratio	30
Upper Stage Engine Expansion Ratio	60
Chamber Pressure	2500 psi
Gas Generator Oxidizer to Fuel Ratio	1.5

The only parameter that was allowed to vary for the engines in this study was the amount of vacuum thrust per engine. The vacuum thrust to weight (T_{vac}/W_e), exit area, and vacuum Isp were calculated using REDTOP-2 version 1.5²⁰. The 1-D curve fits used for T_{vac}/W_e and exit area in the overall vehicle model are shown in through . The Vacuum Isp output did not show any trend to fit a curve so the average outputted Isp for engine type was used, 327.6 sec for the booster, and 338.5 sec for the upper stage. The number of engines can be selected so the engines are appropriately sized for a sea level thrust to weight of 1.2 at liftoff and a vacuum thrust to weight of 1.0 at staging.

3.2.4 Airbreathing Propulsion

The flyback RTLS option makes use of a turbofan engine to cruise back to the launch site after re-entering the atmosphere and turning around. The actual amount of thrust required for the engine at any given point during the cruise is calculated by POST to maintain a constant Mach number and altitude.

The other input required for POST is the Isp of the engine at the cruising altitude which was calculated based on the parameters in the engine performance code PARA version 4.015. Sea-Level thrust, used for sizing the engine mass, was calculated based on the density ratio between cruising altitude and sea-level and the required cruising thrust at the beginning of the flyback cruise calculated by POST. The installed thrust to weight for the turbofan was estimated to be 3.0

3.2.5 Trajectory Simulation

The trajectory simulations were modeled using NASA's 3 DOF Program to Optimize Simulated Trajectories. This is a FORTRAN 77 legacy code very highly used in the spacecraft and launch vehicle industries. The input deck of the trajectory is broken down into different events that begin at user defined triggers and incorporates all aspects of flight including aerodynamics, the curvature and oblateness of the earth, the orientation of the vehicle, velocity losses, etc. The program will integrate along the equations of motion for a given set of user defined input variables. On top of the trajectory analysis, POST can use 1 of 3 methods to optimize the input variables based on a set of user defined dependant variables to achieve a user defined objective function²³.

For the ascent branch and the three different RTLS branches, POST's accelerated projected gradient optimizer was used. Projected Gradient is based on the Method of Feasible Directions optimization scheme in which the optimizer will find a feasible design point and "follow" the constraints to find the optimized value²⁴. The four POST decks used in this study are in Appendix A.

The Ascent Branch deck is common to all three RTLS options. Its objective function is to maximize the burnout weight at a circular 100nmi orbit at 28.5° inclination. The first event is the total configuration taking off vertically from KSC and beginning to pitch over. The pitch angles along the path are optimized based on a linearly interpolated table of time steps. The staging point occurs at an inputted value of ideal change in velocity (ΔV). At this point, the weight of the booster is dropped and the upper stage coasts for 5 seconds before lighting the upper stage engines. The upper stage then flies along optimized pitch angles until reaching orbit velocity at 100 nmi and 0 flight path angle. The engine thrust is throttled to ensure a maximum acceleration of 6 g's. The vector of conditions at staging are wrapped into ModelCenter and passed onto the RTLS branch.

The glideback RTLS branch starts at the staging conditions from the ascent branch with the weight of the booster after staging. The booster flies at zero bank and angle of attack of 45°. The booster coasts to the peak of its trajectory and then re-enter the atmosphere. When the wind loading reaches 2.5 g's, the angle of attack is lowered using POST's generalized acceleration steering, until the dynamic pressure reaches its peak (change in dynamic pressure equals zero). At this point, the booster begins to turn at optimized angles of attack and bank angles. The booster turns until it reaches an optimized azimuth angle and then has 20 seconds to pull out of the turn to a zero bank and an angle of attack for best L/D based on the given aerodynamic model. The POST deck ends when the booster reaches the longitude of the launch site. The independent variables are the angles off attack, turning bank angles, and the azimuth angle to turn to. The constraints are the final latitude, max wing loading of 2.5 g's, and max dynamic pressure of 500 psf.

The flyback RTLS branch flies a constant angle of attack of 50 degrees from the staging point. When it reaches a wing loading of 2.3 g's, the angle of attack is lowered using generalized acceleration steering so as to keep the wing loading constant. Since the booster has not used any RTLS fuel and is heavier than the landing weight, the reduce g-load is used to account for the fact that normal force should be 2.5 times the landing weight and not the weight after staging. The total acceleration increases due to the drag in the axial direction. After the total acceleration drops back to 2.3 g's, which is after the booster phugoid mode altitude, the booster will begin to bank at optimized angles of attack and bank angles. It will keep turning until it reaches the appropriate optimized azimuth angle to fly back to the launch site, take 25 seconds to pull out of the turn, and then will fly at 10° angle of attack (the best L/D ratio for this aero model) and zero bank until it reaches about 16,000 ft. It will then start the engine and pullout to about 15,000 ft. The angle of attack, throttle, and bank angle are then varied using generalized acceleration steering to fly

straight and level until reaching the longitude of the launch site. The independent variables are the angles of attack and bank angles during the turn and the azimuth angle to turn to. The constraints are the final longitude, wing loading, max angle of attack, and dynamic pressure during the turn.

The ascent trajectory for the flyback method was modified to set a staging flight path angle to control the maximum dynamic pressure during re-entry. The flight path angle at staging used to produce the results shown here was 20°.

The boostback RTLS branch begins with the booster pitching around to an angle of attack of 180° so that the thrust is opposite the velocity vector with the rocket engine off with in 10 seconds. One engine is then turned on and the booster flies to an optimal pitch angle and that. The criteria for shutting off the engine was selected to be the horizontal velocity towards the base (POST variable vxf). After shutting off the engine, the booster went to a 40° angle of attack and held that angle until the wing loading reached 2.5 g's, since the booster at this point has undergone the RTLS burn and is now at the landing weight. The angle of attack was then adjusted using generalized acceleration steering to maintain that normal force until the altitude leveled off before the phugoid mode altitude rise. Then the booster glided at optimal pitch and bank angles until reaching the longitude of KSC. The independent variables are inertial pitch angles while the engine is running, and the angle of attack and bank angles during the gliding portion of flight. The constraints are the maximum number of normal g's while gliding, maximum dynamic pressure, a minimum altitude of 15,000 ft at the end of the flight, the final latitude, and a maximum angle of attack of 40° during gliding flight.

3.2.6 Weights and Sizing

Weights and Sizing was set up in Microsoft Excel and was done by breaking up the vehicle into MERs for the booster and upper stage and sizing each stage separately²⁵. The MR for each of the three branches is used to properly size the two stages. The upper stage is first sized by varying the total amount of propellant in the vehicle. The booster is then sized adding in the gross weight of the upper stage by varying the scaling parameter of the baseline dimensions and the total amount of propellant required for the RTLS branch. The sizing parameters are set using Microsoft Excel's Solver so that all required MR and calculated MR are equal. There are no technology reduction factors added to these MERs so that the mass estimation is based on the current state of the technology. The Simple Electrical Systems and Avionics Wizard²⁶ is used to estimate the weight of the avionics required for the booster and the upper stage.

The propulsion weight sizing is based on thrust to weight ratios discussed above. The rocket engines thrust to weight ratios comes from the REDTOP-2 design tool. The airbreathing engine weight was calculated based on an assumed thrust to weight of 3 based on the sea level thrust.

The thermal protection MER used for the booster requires an input of surface area density. The chart shown in Figure 5 shows the surface area density used as a function of maximum re-entry Mach number that occurs after the booster reaches the peak of its trajectory. Below Mach 3, no TPS is needed.

A 15% propellant reserve was used flyback and 1.5% propellant was reserve was used for boostback. The residuals for RTLS were 0.5%. There were 1% propellant reserves and residuals for ascent on each stage. Each stage assumed a 1% startup amount of propellant.

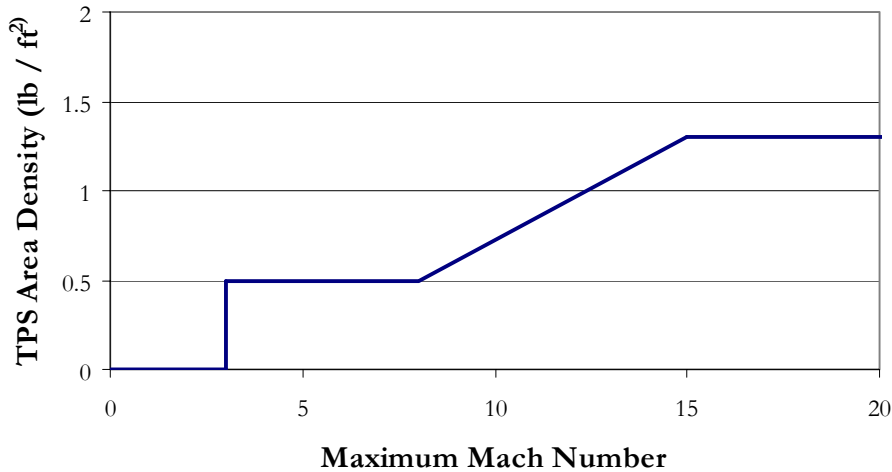


Figure 5. TPS Area Density as a Function of Maximum Re-entry Mach Number.

3.3 Design Structure Matrix and MDO

Each of the contributing analyses fit into a design structure matrix shown in Figure 6. The links on the top right of the CA's are known as the feed forwards and the links on the bottom left are known as the feedbacks. Since it is very difficult, often impossible, to make a computer model with the feedback loops directly, a MDO technique must be utilized to “break” the feedback links. While this DSM encompasses any possible aspect of an launch system with a RTLS booster, not all of the links are needed for each method, i.e. airbreathing engine is only needed for the flyback method.

The MDO technique known as Fixed Point Iteration was used in ModelCenter to handle the feedback. In FPI, guesses are made for the variables that are feedback. All CA and feed forward links are then ran. The outputs from the model are then logged and put back into the model as the new guesses. When the difference between the guesses and the outputs are within some appropriate tolerance, then system is assumed to be converged. The only system variable in this study was the staging ideal ΔV .

The glideback RTLS branch was taken outside of the overall system loop because it does not give any output to the rest of the model because it only tries to maximize the final altitude over the landing site based on the staging conditions. For glideback, the booster and upper stage are sized based on the staging point and the glideback RTLS branch is then run to determine what altitude it will reach over the launch site.

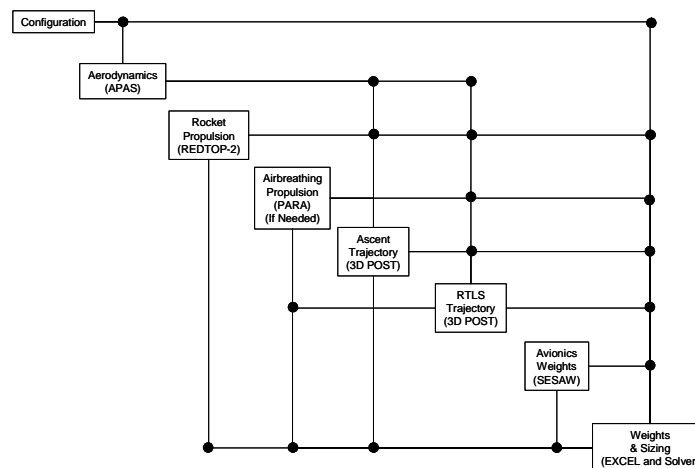


Figure 6. DSM Used for Modeling of the RTLS Methods in this Study.

4.0 Results

4.1 Optimal Staging Points

For the boostback and flyback RTLS methods, a sweep of staging points was run to show where the staging point occurs for lowest gross mass and for lowest dry mass. For glideback, a sweep of staging points was done to find the final altitude after gliding back to the launch site. The sweeps of staging points for gross and dry mass are shown in Figures 7 and 8. For both boostback and flyback, the sweep of staging points show a bucket shape for gross and dry mass show that there is an optimal staging point for minimum mass. For glideback, no optimal point can be selected because there is a cutoff point where the booster can't make it back with the required altitude margin. Table III shows the conditions at the optimal staging point for each of the RTLS methods and the vehicle parameters that results from that staging point.

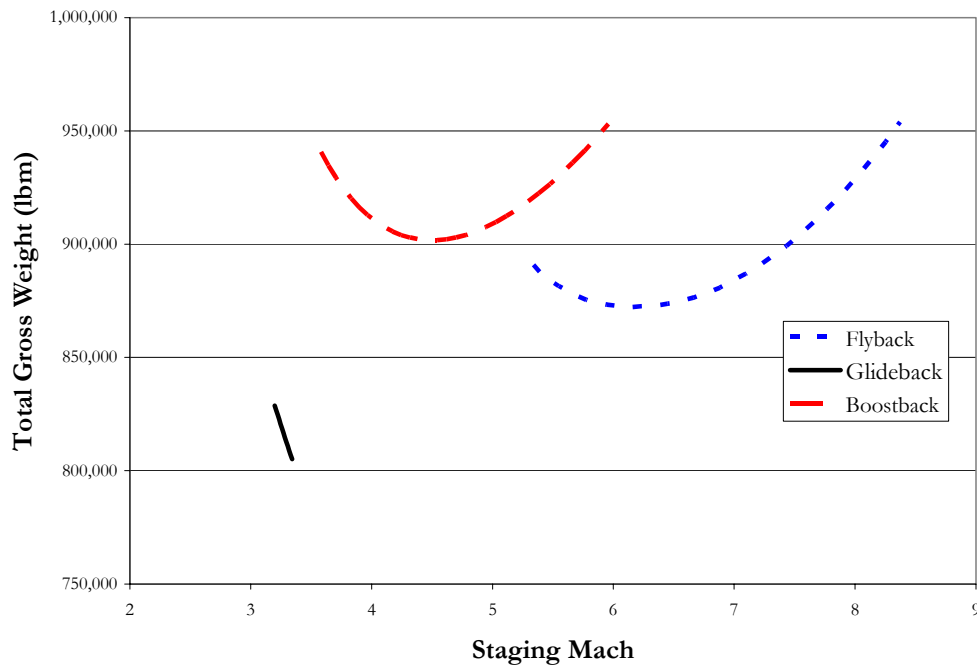


Figure 7. Total Gross Mass of Booster and Upper Stage at Various Staging Points.

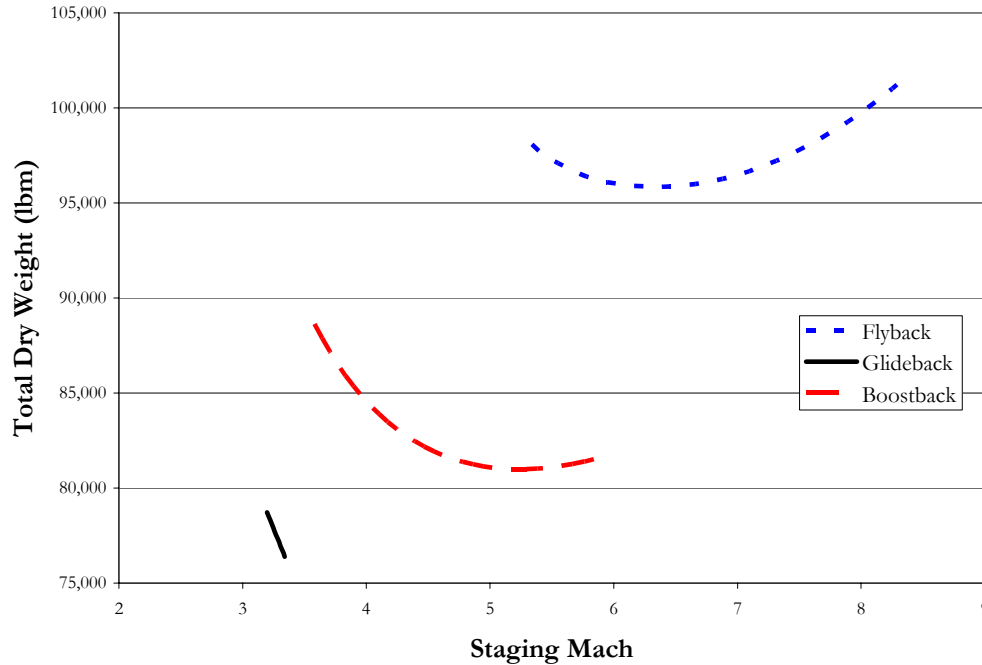


Figure 8. Total Dry Mass of Booster and Upper Stage at Various Staging Points.

Table III. Parameters that Result from Optimal Staging Points.

Optimal Staging Point Parameters	Glideback	Flyback (Lowest Gross Mass)	Boostback (Lowest Gross Mass)	Flyback (Lowest Dry Mass)	Boostback (Lowest Dry Mass)
Staging Ideal ΔV (ft/sec)	7,248	11,000	9,300	11,200	10,200
Staging Mach Number	3.23	6.15	4.47	6.35	5.20
Staging Velocity (ft/sec)	3,226	6,588	4,801	6,759	5,594
Staging Altitude (ft)	106,944	174,622	153,921	178,938	172,224
Staging FPA (deg)	44.6	20.0	34.9	20.0	31.0
Max Re-Entry Mach	1.86	6.67	2.45	6.93	2.72
Total Gross Mass (lbm)	822,632	872,175	901,712	872,766	915,317
Total Dry Mass (lbm)	78,117	95,896	82,184	95,838	80,983
Booster Length (ft)	74.4	85.4	82.4	85.7	84.9
Upper Stage Length (ft)	80.0	72.7	73.9	72.6	73.2
RTLS Time (sec)	846	4426	665	4651	750

4.2 Trajectory plots

4.2.1 Glideback Trajectory

As shown above, the staging condition that allows for the booster to have a final altitude of 15,000 ft above the launch site occurs at about Mach 3.1. The altitude vs. downrange plot of the trajectory is shown in Figure 9. Figures 10 and 11 show the important flight parameters during the glideback trajectory. The booster reaches a peak altitude of about 31 nmi, re-enters the atmosphere, and then turns south for returning. The turn begins when the booster is supersonic and ends after it has dropped below Mach 1. During its turn, it reaches a maximum downrange distance of about 52 nmi. It begins the straight glide under Mach 0.8 and decelerates until it reaches the launch site. Since the peak re-entry Mach number of 1.86 (the peak in Figure 11) is well below Mach 3, no TPS is required for this method. The ground track for glideback and the other RTLS methods below show that when launch out of KSC, there is no need to modify the trajectory to avoid over-flight issues. The booster returns about 14 minutes after staging.

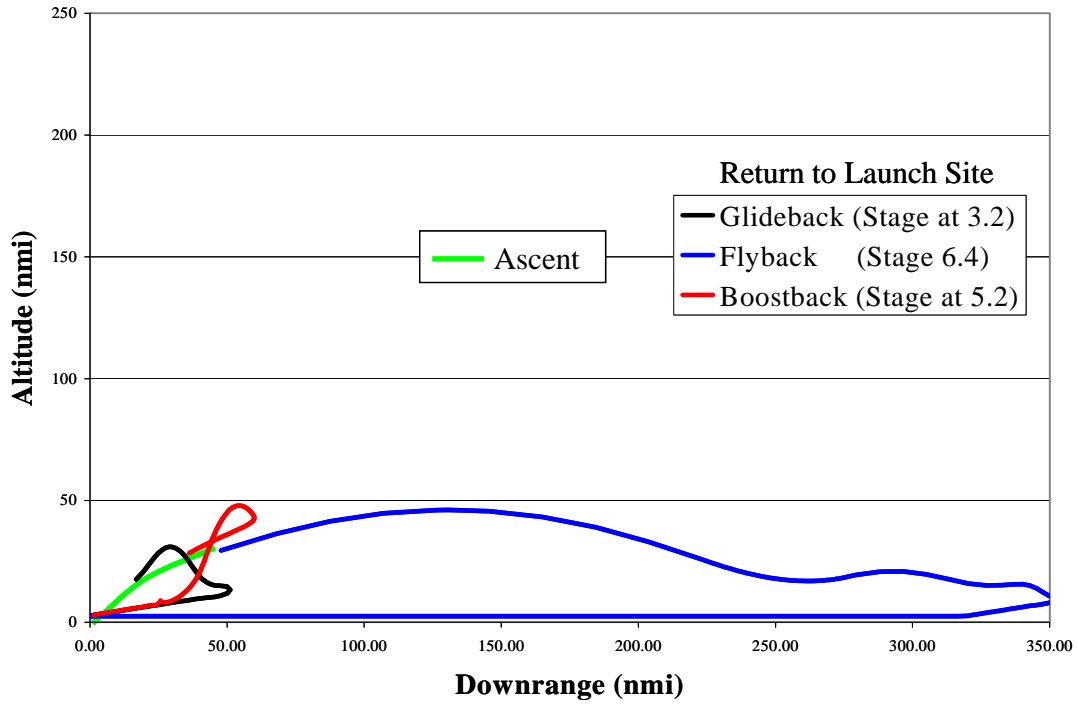


Figure 9. Altitude vs. Downrange for each RTLS Method.

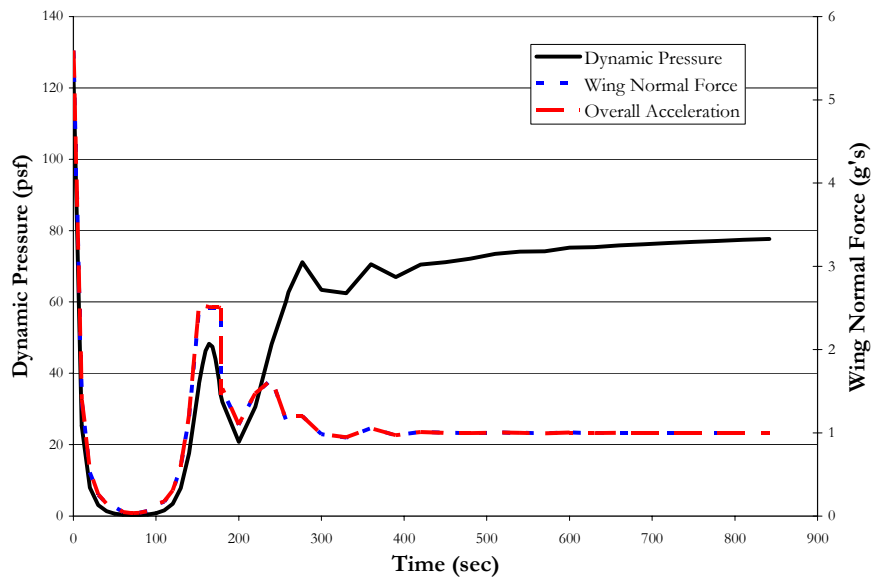


Figure 10. Dynamic Pressure, Normal Force, and Overall Acceleration vs. Time for Glideback Trajectory.

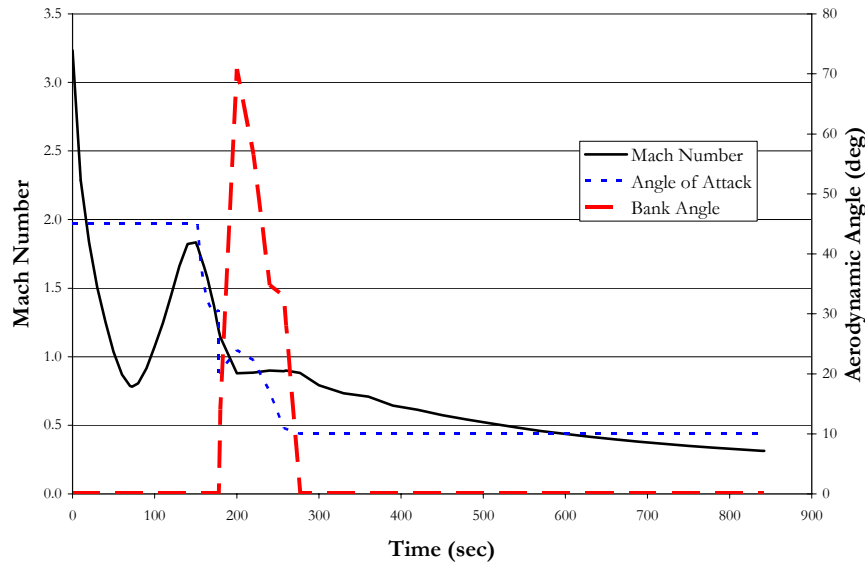


Figure 11. Mach Number and Aerodynamic Angles for Glideback Trajectory.

4.2.2 Flyback Trajectory

Figures 9, 12, and 13 show the booster’s trajectory for the optimal dry weight flyback method. The booster reaches a peak altitude of about 48 nmi. As it re-enters the atmosphere, the angle of attack is dropped rapidly and then is increased to hold the required normal force until the phugoid mode altitude rise occurs. At the peak of the altitude rise, the booster begins its gliding turn in which the booster’s speed is subsonic. The booster reaches a maximum downrange of about 350 nmi. After gliding about 30 nmi (which is about the max downrange distance for the glideback booster), the airbreathing engine must be turned on to hold an altitude of about 15,000 ft. The engine’s Isp is about 3610 sec requiring about 8,000 lbf of thrust for each engine at the beginning of the cruise. The RTLS branch takes about 77 minutes with re-entry Mach number is about 6.93, requiring TPS.

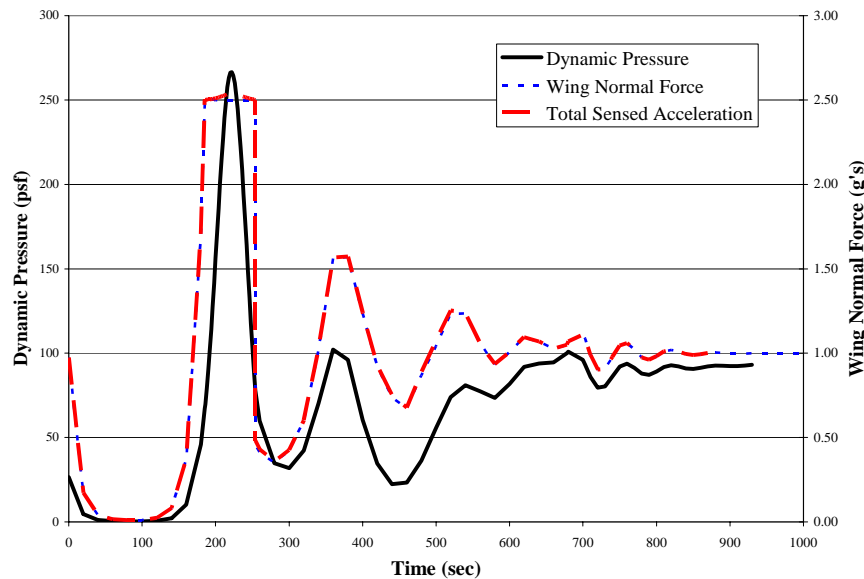


Figure 12. Dynamic Pressure and Mach Number vs. Time for Flyback Trajectory.

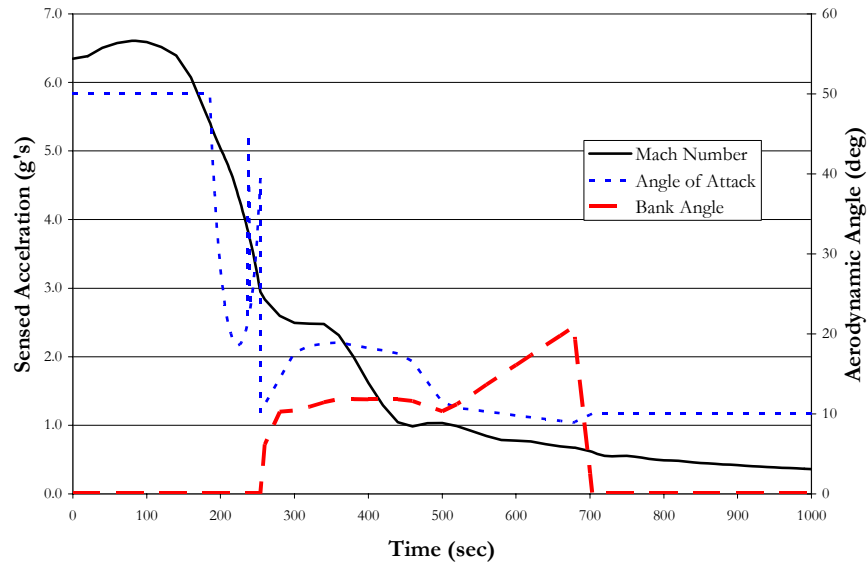


Figure 13. Normal Acceleration and Aerodynamic Angles for Flyback Trajectory.

4.2.3 Boostback Trajectory

The trajectory of the optimal dry weight booster using the boostback RTLS method is shown in Figures 9, 14, and 15. The booster maximum downrange is about 24 nmi which is less than the glideback trajectory. This effect is due mostly to the reverse engine thrust providing more deceleration than and aerodynamic turn. Also the deceleration can start occurring above the atmosphere, which a glideback maneuver cannot due. The peak of the trajectory is at 28 nmi. During the engine burn, the angle of attack is very high to allow for the thrust vector to be opposite the velocity vector. After the engine burn, the booster is a dive like state when re-entering, and levels off after the peak deceleration. The maximum re-entry Mach number is below 3 so no TPS is required. After the phugoid mode altitude rise, a mild amount of banking is required to line up the booster with the launch site. The time of flight for the boostback RTLS branch is about 3 minutes. When the booster reaches the launch site, it is well over 15,000 ft in altitude giving plenty of margin to land.

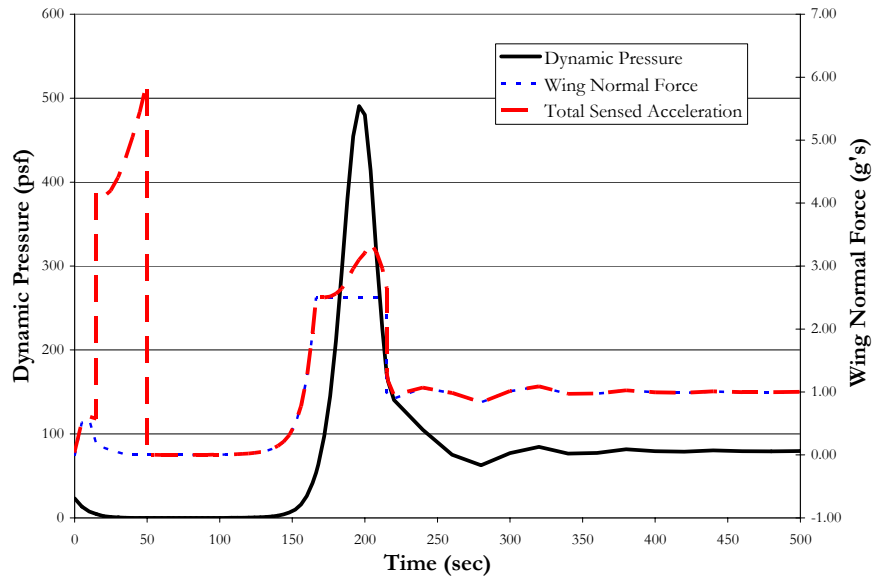


Figure 14. Dynamic Pressure and Normal Force vs. Time for Boostback Trajectory.

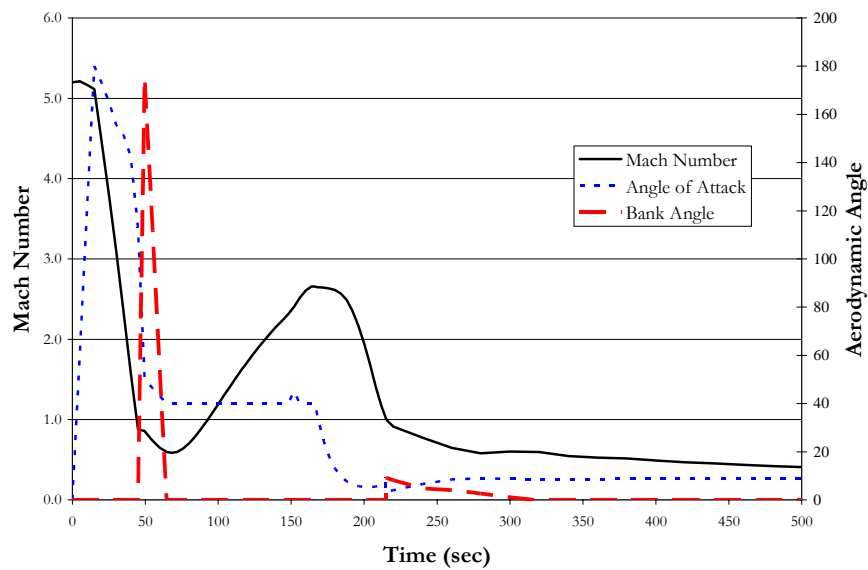


Figure 15. Mach Number and Aerodynamic Angles for Boostback Trajectory.

5.0 Discussion and Conclusions

The booster used in this study is a simple design consisting of a circular fuselage with a dropped nose, integral propellant tanks, and wing with vertical fins attached to the wing tips. The upper stage is expendable and mounted on top of the fuselage. This winged structure for the booster allows for large amounts of crossrange control that are needed to for turning and landing back at the launch site. The wings are also necessary to decelerate and provide lift during the steep angle re-entry that result from a ballistic trajectory after the staging point. Even though this type of booster is necessary to execute the RTLS methods analyzed in this study, it will weigh more than an expendable booster with the same mass ratio, resulting in higher development and manufacturing costs. The additional weight comes with the

extra systems required for RTLS such as wings, landing gear, and TPS if required. Even though the upfront costs for a reusable booster will be higher than an expendable one, the recurring costs should make the investment worth while, assuming that the launch frequency is high enough.

The glideback RTLS method is the simplest method and doesn't require any additional propellant after staging. After re-entering the atmosphere, it turns more than 180° and is able to reach the landing site with enough altitude margin without any additional energy. The highest staging point is about Mach 3.1, which gives a low enough re-entry Mach number thereby removing the need for TPS and a very large recurring maintenance cost. This low staging Mach number causes the upper stage to have a longer fuselage than the booster, which is consistent with previous studies⁵. During re-entry the overall acceleration of the booster doesn't get much higher than that in the normal direction, possibly allowing lighter wings. Since there is no extra propellant on board, it re-enters at the same weight it lands with. Although the vehicle is not able to control the downrange distance of re-entry, the low staging point allows for maximum downrange point of less than 55 nmi and only requires 14 minutes to reach KSC after staging. As was also shown, the final altitude that glideback booster can reach over the launch site drops very rapidly over with only small increases in staging Mach number. In order to maintain proper altitude margin, the glideback trajectory has very little margin. Minor adverse weather condition may limit the number of launch opportunities available. Furthermore, the vehicle may have more limited capabilities at other launch sites due to overflight limitations. The staging point for glideback is similar to what was estimated in other studies.

The flyback RTLS method requires the most change and complexity to the baseline booster presented. It requires an additional fuel tank and hardware for turbofan engines that add to the dry weight and reduce the packaging efficiency. Its optimal staging point is the highest of the methods analyzed. After staging it has no control over the downrange distance for re-entry and reaches about 350 nmi during its turn. This method must re-enter with a higher weight than when it lands due to the fuel needed for flyback; thus, preventing the booster from allowing the full 2.5 normal g's. The re-entry Mach number requires some modest TPS that adds to dry weight and requires maintenance. During re-entry, the booster only experiences a brief 3 g's of overall acceleration. After turning the booster glides for about 35 nmi (a little less than glideback) before turning on the engine. The 15% fuel reserves it carries can help in adverse weather conditions. Since the boosters take about an hour to return, this margin is needed since weather concerns must be addressed. The staging point in this study is lower than most previous studies.

The boostback RTLS method utilizes one of the ascent engines on the booster to slow down near at apogee and start the booster gliding in a direction pointing near the launch site. This prevents the need for extra hardware or an extra fuel tank, keeping the packaging efficiency the same as glideback. The propellant needed for the boostback burn comes from the same tanks as what was used for ascent. The optimal staging point occurs slightly higher than glideback and lower than the Kister K-1. After staging, the booster pitched around so that thrust vector points opposite the velocity vector. The engine must be relit. The booster flies above the ascent trajectory before beginning the glide. The booster enters at its landing weight and at a Mach number low enough to avoid the need for TPS. A small amount of banking is necessary to get back to the launch site's latitude. Out of the three methods, it stays the closest to land with a max downrange distance of about 25 nmi. It also ends with a huge altitude margin, much more than the minimum constraint of 15,000 ft for this study. More analysis needs to be done to show how much margin is available for engine restart when beginning the boostback maneuver. Also, a look into the separation dynamics and the next few moments of flight is needed to ensure that the boostback maneuver doesn't cross the upper stage's path.

Some basic similarities arise between modeling these three RTLS methods. First, they all need very detailed control of the angle of attack during re-entry to ensure that the limit of normal g's is maintained. POST's generalized acceleration steering accomplished this requirement. Also during each RTLS trajectory branch, the most difficult constraint to satisfy was the normal acceleration limit during any gliding portion of the flight.

This study showed that glideback method results in the lowest total gross and dry mass when compared to the others, which is in contrast to the other comparison studies presented. The main reason behind this inconsistent result is that the upper stage in the previous two studies was reusable as opposed to being expendable. Reusable vehicles require significantly more dry mass especially if it reaches orbit, requiring TPS. This extra weight in upper stage caused the booster to grow more and leading to glideback becoming the less preferred method. Thus glideback is only projected to be advantageous on weight criteria if the upper stage is sized only to place the payload into orbit. If a glideback system like the one presented here was built, the same architecture might not be able to be used if the upper stage become reusable.

The boostback method was shown to have an optimal dry lower than the flyback method but a higher optimal gross mass. This can be attributed to a number of reasons. First, flyback requires more hardware for the turbofan engine and fuel tank. The packaging efficiency is also lower with flyback. Boostback, requires a large amount of propellant for the RTLS maneuver which causes the high gross weight. Finally, another reason that boostback is more attractive with the criteria of weight is that no TPS is needed.

For a RTLS booster, boostback provides some distinct advantages in addition to the lower mass. First, it is a much simpler design as it uses the same hardware for ascent as for RTLS maneuvers. It also provides a huge altitude margin over the launch site to ensure a safe landing. Its downrange distance is very short allowing it to return quickly before the conditions at the launch site become more difficult for landing.

In order to better understand which RTLS method is better, an optimization of other design variables such as upper stage diameter and engine parameters needs to be done. Also, a look at the separation dynamics for each method will help improve the overall trajectory modeling. Lastly, another area that needs to be addressed in the minimum cost for each RTLS method. The total dry weight cannot accurately estimate the life cycle cost of a hybrid system to the uniqueness of the architecture. The upper stage for TSTO hybrid system is thrown away every launch while the booster is reused. The development cost of the booster will be higher than the upper stage but it is amortized over the number of flights it will be flown. Taking these cost aspects into account will most likely lead to a higher staging point so the upper stage can be made smaller as it expendable.

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