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HYPERBOLIC RENDEZVOUS AT MARS: RISK ASSESSMENTS AND MITIGATION STRATEGIES

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Given the current interest in the use of flyby trajectories for human Mars exploration, a key requirement is the capability to execute hyperbolic rendezvous. Hyperbolic rendezvous is used to transport crew from a Mars centered orbit, to a transiting Earth bound habitat that does a flyby. Representative cases are taken from future potential missions of this type, and a thorough sensitivity analysis of the hyperbolic rendezvous phase is performed. This includes early engine cut-off, missed burn times, and burn misalignment. A finite burn engine model is applied that assumes the hyperbolic rendezvous phase is done with at least two burns.

INTRODUCTION

Crewed missions to Mars require the transfer of very massive payloads. Capturing and departing massive payloads at large celestial bodies requires tremendous amounts of propellant. High propellant requirements lead to dramatically higher mission costs. In an effort to minimize mission mass, new Mars mission architectures have been evolving that utilize flyby trajectories and hyperbolic rendezvous.[1, 2] Cycler trajectories that have been discussed previously also require the execution of hyperbolic rendezvous.[3] The utilization of hyperbolic rendezvous can significantly reduce the payload mass that needs to capture and depart from orbit around large celestial bodies. Classical strategies that place a more massive vehicle, dedicated to the entire mission, into a captured Mars orbit require significantly more propellant. In contrast, hyperbolic rendezvous enables the use of smaller transportation only service modules, referred to throughout this paper as taxi vehicles, to transfer the crew to pre-emplaced mission elements.

The Mars Lite team, comprised of the Johnson Space Center (JSC) Human Architecture Team (HAT) together with support from the Jet Propulsion Laboratory (JPL), studied the characteristics of hyperbolic rendezvous. This study investigated what factors of hyperbolic rendezvous affect vehicle mass and propellant requirements the most. Some of the parameters examined are hyperbolic excess velocity, periapsis altitude, and the transfer time for Mars orbiting assets to depart orbit and rendezvous with the Earth bound habitat. Also, since this is an orbital maneuver that has not been attempted before, this study also investigated the risks associated with hyperbolic

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rendezvous, and what strategies can be implemented to reduce those risks. Some of the risks examined include early engine cutoff, missed burn times, and burn misalignment. Some strategies that have been devised to mitigate the aforementioned risks include adjusting the timing of the nominal Mars departure burn, allowing for additional burns, and adjusting the nominal Mars centered parking orbit.

This paper presents the practicality of using hyperbolic rendezvous in future crewed mission to Mars. The greatest impacts to vehicle performance, risk factors, and strategies are outlined. Multiple contingencies to avert risk and safely perform a hyperbolic rendezvous mission are introduced. The focus on this paper are the orbital mechanics and characteristics of a hyperbolic rendezvous. The implications of proximity operations during a hyperbolic rendezvous are beyond the scope of this paper, although some of these implications have been addressed elsewhere[4].

OVERVIEW OF HYPERBOLIC RENDEZVOUS PHASE AND METHODOLOGY

Unlike previously performed rendezvous operations, a hyperbolic rendezvous has at least one vehicle on a hyperbolic trajectory. The greatest implication of hyperbolic rendezvous is that there is only one opportunity to depart a closed orbit and rendezvous before the vehicles' range diverges indefinitely. The following nomenclature and assumptions will be used throughout the studies conducted in this paper.

The studies conducted in this paper are built around the following assumptions. Two vehicles are modeled during the hyperbolic rendezvous phase. One vehicle is based in an elliptical orbit around Mars. The vehicle orbiting Mars is referred to as the taxi vehicle. The taxi vehicle is assumed to be the only active vehicle during the hyperbolic rendezvous, meaning it is the only vehicle performing maneuvers. Unless stated otherwise, the taxi vehicle performs 2 burns. The first burn leaves Mars orbit, the second burn is used to rendezvous. Near field proximity operations are not considered in this paper. The second vehicle, referred to as the transit habitat or vehicle, is the vehicle along the Mars hyperbolic trajectory. The transit habitat is a passive vehicle, and does not perform any maneuvers.

The primary tool used in this study is the Copernicus Trajectory Design and Optimization System. A finite burn engine model is applied that assumes the complete hyperbolic rendezvous phase is done with at least two burns. The finite burns are modeled with an in plane and out of plane angle that is fixed relative to a specified frame throughout the burn. The 2 control frames utilized are velocity vector and inertial steering. It is assumed that there are no errors in the knowledge of both vehicles' current location and velocity.

There are four major events involved in a hyperbolic rendezvous. These events are outlined below.

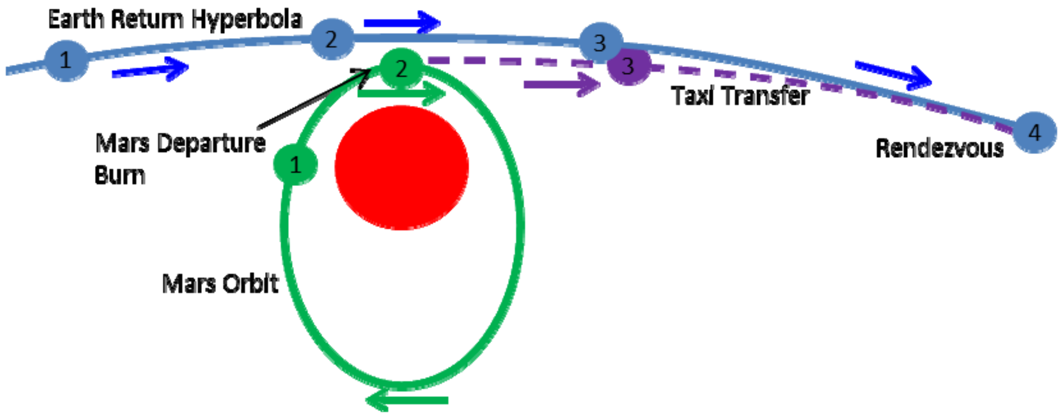

Figure 1. Hyperbolic Rendezvous Events.

1. The transit habitat and taxi vehicles approach periapsis.
2. The taxi vehicle performs the Mars orbit departure burn.
3. Range between the taxi and transit habitat begins to decrease.
4. A final rendezvous burn is performed by the taxi vehicle.

These studies assumed Mars and Sun point mass gravity models. In some cases as will be indicated, an 8x8 Mars gravity model, GMM2B, is applied. Minimum altitude constraints are not enforced. For burns that occur prior to periapsis, the vehicle may pass through an altitude lower than the periapsis. Other relevant assumptions, such as the hyperbolic excess velocity (V_∞) used, taxi vehicle orbit size, etc., are presented for each study conducted. The states presented are of the state immediately prior to the taxi vehicle's Mars departure burn unless stated otherwise. The range of these parameters are characterized by the range of values gathered in the mission opportunities examined by the Mars Lite team[5].

HYPERBOLIC PARAMETERS DRIVING VEHICLE PERFORMANCE

Hyperbolic parameters were varied to measure their impact total Delta Velocity (DV) of the hyperbolic rendezvous phase. Figure 2, 3, and Table 1 show hyperbolic rendezvous vehicle performance for various nominal cases.

Table 1. Sample hyperbolic rendezvous cases.

V_∞ (km/s)	Flyby Altitude (km)	Catch Up Time (days)	Total DV Required (m/s)
2.612	500	7	893
2.612	500	1	895
2.612	10,000	1	995
2.713	10,000	7	959
4.565	533	7	2,134

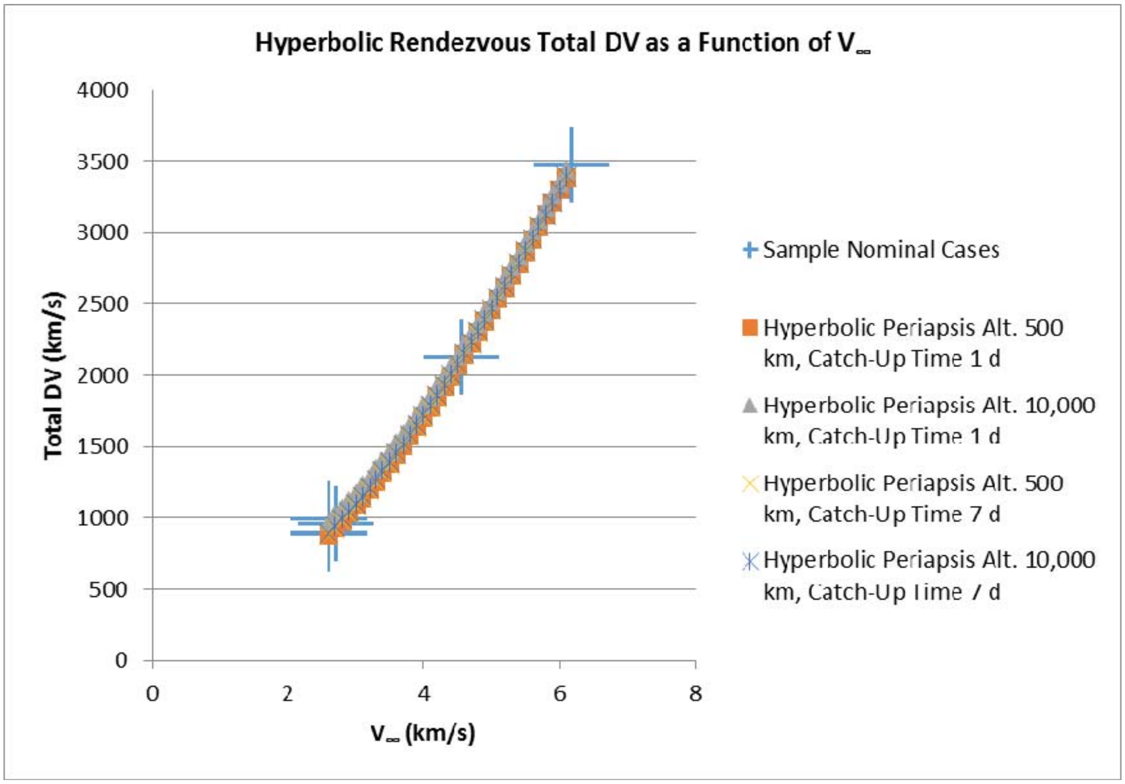

Figure 2. Required DV for various hyperbolic rendezvous parameters.

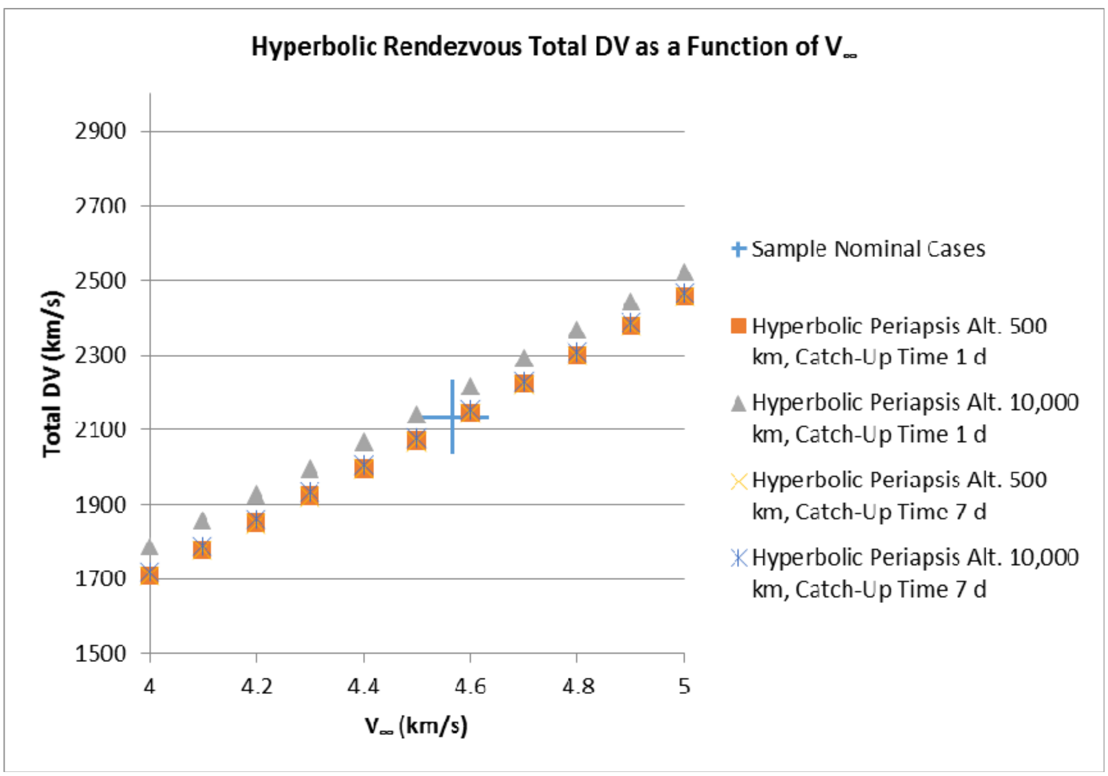

Figure 3. Required DV for various hyperbolic rendezvous parameters zoomed in.

V_∞ refers to the hyperbolic excess velocity, and Alt. to altitude. Many of the assumptions used in creating these cases are outlined in the OVERVIEW OF HYPERBOLIC RENDEZVOUS PHASE AND METHODOLOGY Section. The initial state used for the transit vehicle is shown in Table 2 in 2 different parameterizations.

Table 2. Nominal cases transit vehicle initial state.

Parameter (Mars J2000)	Transit Vehicle	Parameter (Mars J2000)	Transit Vehicle
V_∞ (km/s)	Independent Variable	Periapsis Altitude (km)	500 – 10,000
V_∞ Right Ascension (deg)	-151	Eccentricity (-)	Independent Variable
V_∞ Declination (deg)	-15	Inclination (deg)	27
RAAN (deg)	-4	RAAN (deg)	-4
Periapsis Altitude (km)	500 - 10,000	AOP (deg)	144
True Anomaly (deg)	0	True Anomaly (deg)	0

The Right Ascension of the Ascending Node is abbreviated by RAAN, the Argument of Periapsis by AOP. This state is based on a sample nominal trajectory produced by the Mars Lite team[5].

Table 3 shows the initial state used by the taxi vehicle.

Table 3. Nominal cases taxi vehicle initial state.

Parameter (Mars J2000)	Taxi Vehicle
Period (days)	1
Periapsis Altitude (km)	125
Inclination (deg)	Optimized
RAAN (deg)	Optimized
Argument of Periapsis (deg)	Optimized
True Anomaly (deg)	Optimized

The scope of the Mars Lite Team did not involve in-depth sizing of the taxi Mars parking orbit. For ease of comparison, the orbit dimensions were based on NASA'S Design Reference Architecture (DRA) 5.0[6]. For simplicity, a period of 1 day was assumed since the Mars rotation time is only 0.026 days, or about 40 minutes, longer. At periapsis, this amounts to a velocity difference of only 3.8 m/s, which is negligible when examining DV's in the thousands of m/s range. The other parameters were all allowed to vary and be optimized for each case to ensure the optimal solution was produced.

Analyzing these various characteristics indicates that the driving influence in the required DV for hyperbolic rendezvous is V_∞. Hyperbolic periapsis altitudes bound between 500 and 10,000 km, as well as catch-up times between 1 to 7 days have a negligible effect. Figure 4 further shows the small effect these periapsis altitudes have on the required DV across various V_∞ values.

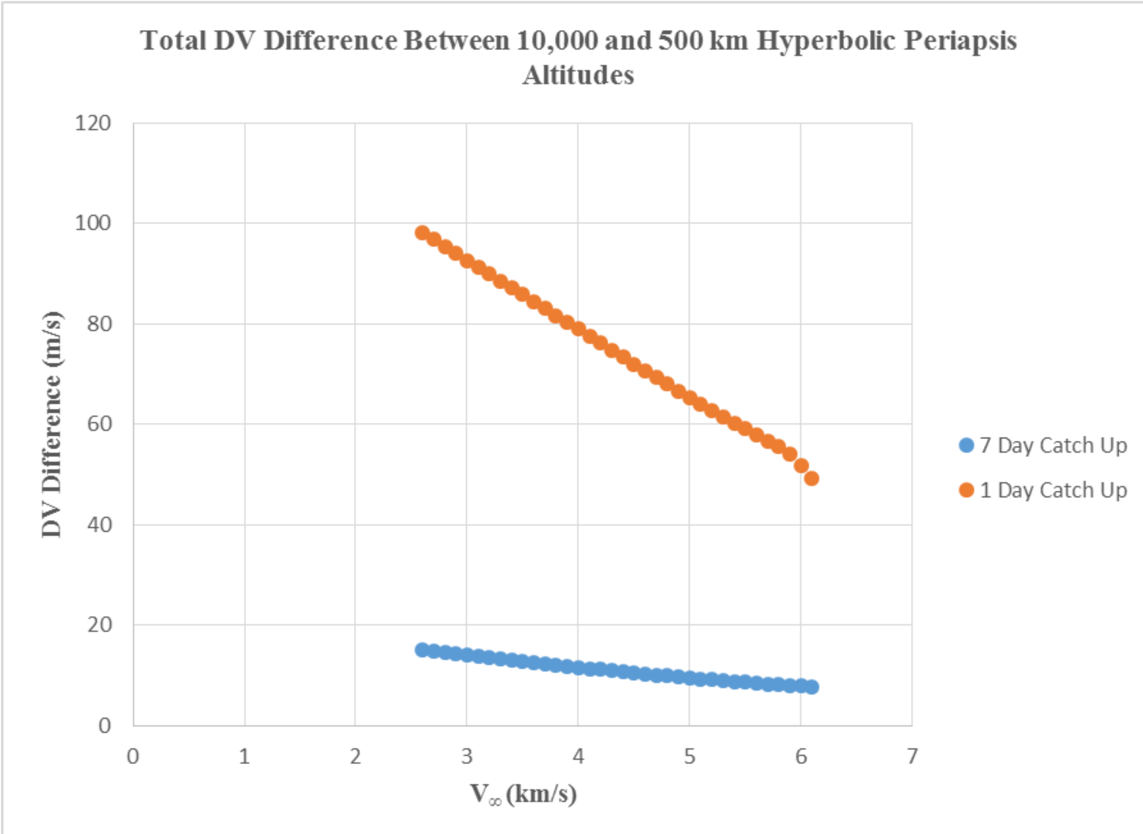

Figure 4. Hyperbolic periapsis altitude effect on required DV.

Compared to the total DV required for hyperbolic rendezvous, it can be seen that the hyperbolic periapsis altitude is not a major contributor. The altitude's greatest component is for low V_∞ values with a short catch up time. This makes sense since a higher hyperbolic periapsis would require more DV to twist the velocity vector through a higher angle. As the V_∞ values increases, this twist becomes less and less of a factor. At higher hyperbolic periapsis altitudes (where the twisting factor has the greatest influence), it only makes up 10% of the total DV.

The amount of time permitted to allow for the taxi vehicle to catch up has many repercussions on vehicle sizing. A long catch up time will lead to more complex environmental control systems, the amount of consumables required, among other things. Shorter catch up times will require more propellant to achieve a greater range rate. The following figures summarize the impact variable catch up times have on the required hyperbolic rendezvous DV.

These variable catch up time studies are also based on nominal cases produced by the Mars Lite Team[5]. The assumptions in the OVERVIEW OF HYPERBOLIC RENDEZVOUS PHASE AND METHODOLOGY Section are still applied here. The initial states of the taxi and transit vehicles are provided below.

Table 4. Initial state of transit vehicle for variable catch up time scan.

Parameter (Mars J2000)	Transit Vehicle	Parameter (Mars J2000)	Transit Vehicle
V_∞ (km/s)	5.055	Periapsis Altitude (km)	625
V_∞ Right Ascension (deg)	-97	Eccentricity (-)	3.399
V_∞ Declination (deg)	-31	Inclination (deg)	146
RAAN (deg)	-159	RAAN (deg)	-159
Periapsis Altitude (km)	625	AOP (deg)	-173
True Anomaly (deg)	0	True Anomaly (deg)	0

Table 5. Initial state of taxi for variable catch up time scan.

Parameter (Mars J2000)	Taxi Vehicle
Period (days)	3
Periapsis Altitude (km)	118
Inclination (deg)	Optimized
RAAN (deg)	Optimized
Argument of Periapsis (deg)	Optimized
True Anomaly (deg)	Optimized

When these scans were conducted, the Mars Lite team was considering departing Mars from a 3 sol orbit. To be consistent with previous assumptions, an orbital period of 3 days was used for simplicity again. In this larger orbit, the difference in velocity at periapsis is now only 1.8 m/s. Below are figures depicting the effect catch up time has on the hyperbolic rendezvous DV.

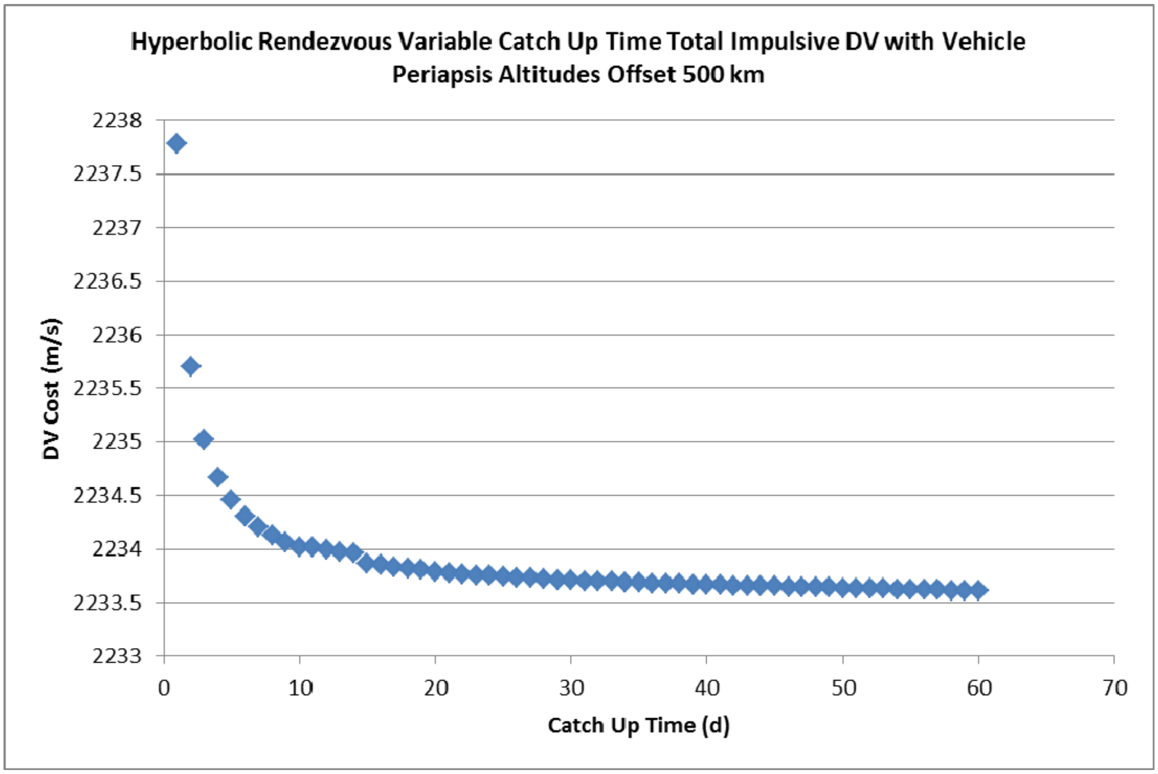

Figure 5. Impulsive DV cost for variable catch up times between 1 and 60 days.

The unit d refers to days. Figure 5 shows the impact catch up time has on total DV. While there is a spike in total DV as the catch up time approaches 0, the scale of Figure 5 shows the bounds are within 5 m/s. Later, the impact of a catch up time on the order or hours is shown. Before examining the impact of shorter catch up times, the effect of finite burns was examined.

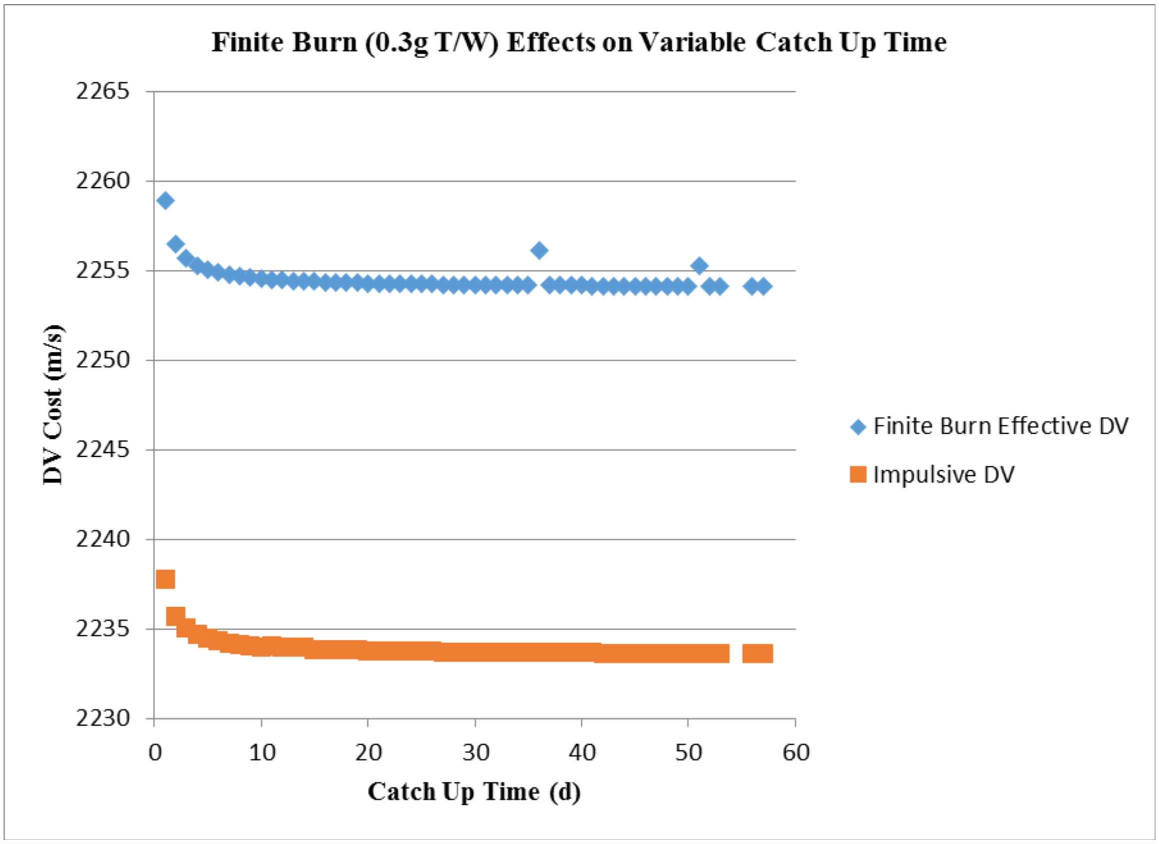

Figure 6. The effect of finite burns on total DV.

As expected, the DV associated with finite burns is higher than the impulsive DV. The Thrust-to-Weight (T/W) ratio was selected as a typical value. The points within the finite burn curve that do not follow the trend are considered outliers and are probably the result of unexpected behavior within the optimization. Those points can likely be corrected to follow the trend. The impact of shorter catch up times and a lower T/W ratio was examined next.

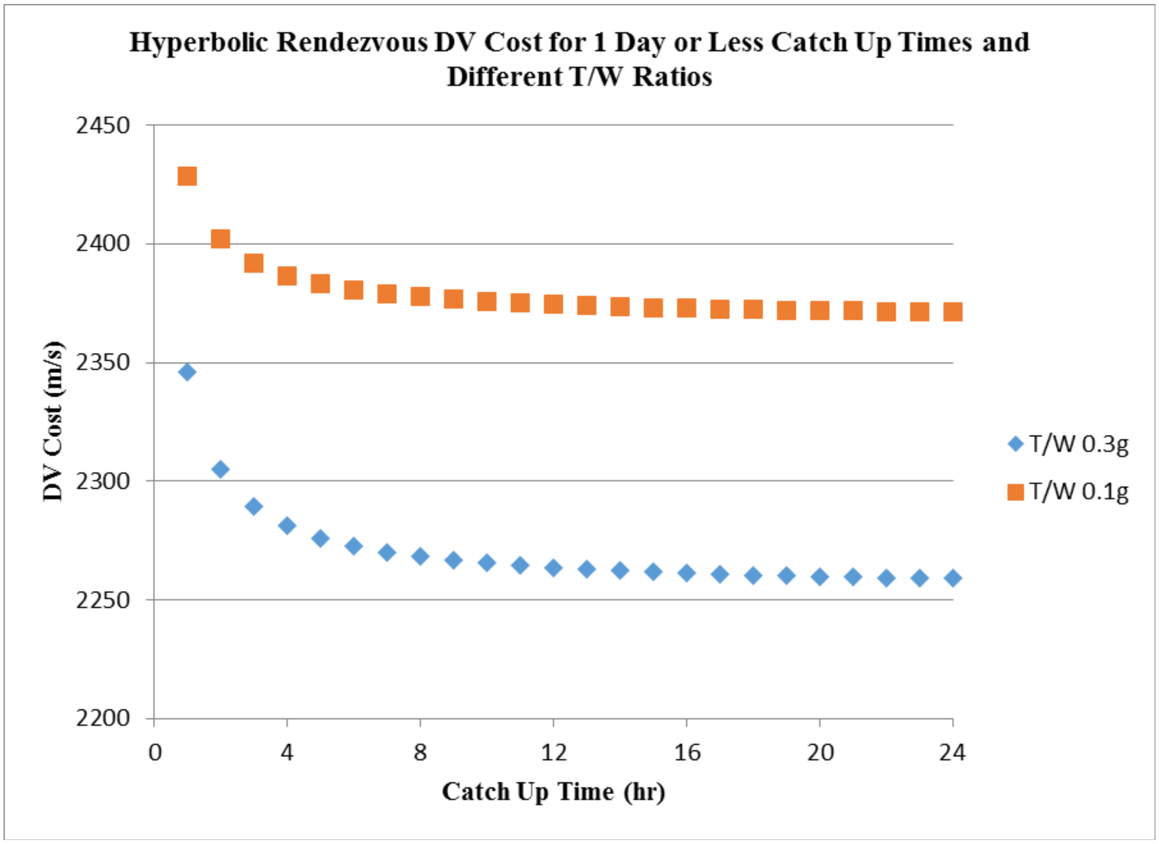

Figure 7. DV cost for catch up times less than a day, with different T/W ratios.

The unit g refers to units of Earth gravitational acceleration. As Figure 7 indicates, once the catch up time gets less and less, the impact on the total DV becomes significant. If the catch up time is allowed to be 60 days, the total DV is 2254 m/s. At 1 day, the cost is 2259 m/s, only 5 m/s higher. However, at 1 hour, the cost is now 2346 m/s, 92 m/s more than the cost to catch up in 60 days. The trends in the above figures clearly indicate that longer catch up times have diminishing returns on total DV. A difference of 92 m/s may also be insignificant compared to the mass savings that a 1 hour vehicle may have in environmental systems and consumables over a 24 hour vehicle. However, accounting for contingency scenarios is also important. Several contingencies are discussed in the OFF NOMINAL DEPARTURE SCENARIOS AND IMPACTS Section.

OFF NOMINAL DEPARTURE SCENARIOS AND IMPACTS

The main concern with incorporating hyperbolic rendezvous into missions is the notion of only having 1 opportunity to rendezvous. Unlike typical rendezvous, where both spacecraft are orbiting the same body, in a hyperbolic rendezvous at least one spacecraft is on a trajectory that will constantly increase in range if the rendezvous were missed (not considering cyclers or similar trajectories that will return significantly later, likely years for a Mars mission). Not only does the impact of the taxi vehicle missing its burn need to be assessed, but so do other off nominal scenarios such as a slipped Time of Ignition (TIG) and under speeds.

Impacts of Varying the Taxi Mars Departure Time of Ignition

One major sensitivity to understanding major maneuvers, is the impact of off nominal burn TIG. To understand the impact on hyperbolic rendezvous, 2 different circumstances are examined. First, the impact of the TIG slipping by seconds or minutes is examined. Then, the impact of the taxi vehicle performing its Mars departure burn entire revolutions late is examined.

It is not uncommon for a burn TIG to slip by seconds or minutes during a mission. Therefore, it is very important to identify how this can impact the DV requirement and risk of hyperbolic rendezvous.

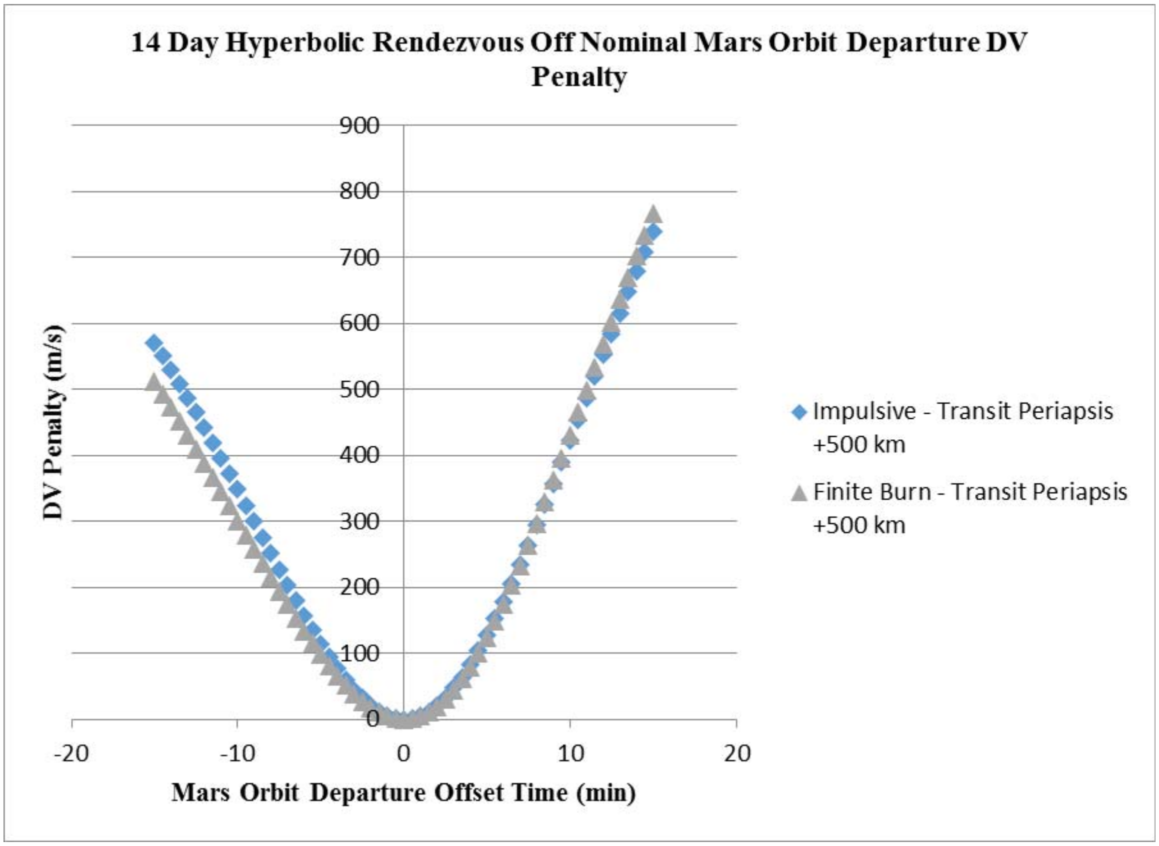

Figure 8. The impact of slipping the Mars departure TIG by minutes.

DV refers to the Delta Velocity. These cases were produced with many of the assumptions presented in the OVERVIEW OF HYPERBOLIC RENDEZVOUS PHASE AND METHODOLOGY Section. The initial states assumed for the transit and taxi vehicles are as follows.

Table 6. Initial state of the transit vehicle used for examining TIG slip.

Parameter (Mars J2000)	Transit Vehicle	Parameter (Mars J2000)	Transit Vehicle
V_∞ (km/s)	5.055	Periapsis Altitude (km)	625
V_∞ Right Ascension (deg)	-97	Eccentricity (-)	3.399
V_∞ Declination (deg)	-31	Inclination (deg)	147

RAAN (deg)	-159	RAAN (deg)	-159
Periapsis Altitude (km)	625	AOP (deg)	-173
True Anomaly (deg)	0	True Anomaly (deg)	0

Table 7. Initial state of the taxi vehicle used for examining impulsive TIG slip.

Parameter (Mars J2000)	Taxi Vehicle
Period (days)	3.0
Periapsis Altitude (km)	118
Inclination (deg)	144
RAAN (deg)	-153
Argument of Periapsis (deg)	-168
True Anomaly (deg)	-59

V_∞ refers to the hyperbolic excess velocity, RAAN is the Right Ascension of the Ascending Node, and AOP is the Argument of Periapsis. As before, the transit vehicle's initial state was based on a sample Mars-Earth hyperbolic trajectory. The taxi's initial state was fixed to the optimal trajectory's corresponding state. The taxi's initial state for finite burns is included in Table 8.

Table 8. Initial state of the taxi vehicle used for examining finite burn TIG slip.

Parameter (Mars J2000)	Taxi Vehicle
Period (days)	3
Periapsis Altitude (km)	118
Inclination (deg)	144
RAAN (deg)	-152
Argument of Periapsis (deg)	-170
True Anomaly (deg)	-71

Like the title of Figure 8 indicates, these cases allowed for 14 days of catch up time. Given the results shown in Figure 6, different catch up times will not have a significant impact, unless they become shorter than 1 day. However, Figure 8 should be reproduced with different catch up times to verify the impact (or lack thereof) of different catch up times on TIG slips.

Perhaps one of the greatest concerns with hyperbolic rendezvous is the risk associated with the taxi missing its Mars departure burn altogether, and having to wait at least 1 additional revolution around Mars. Figure 9 shows how significant the impact of the taxi missing its Mars departure burn can be.

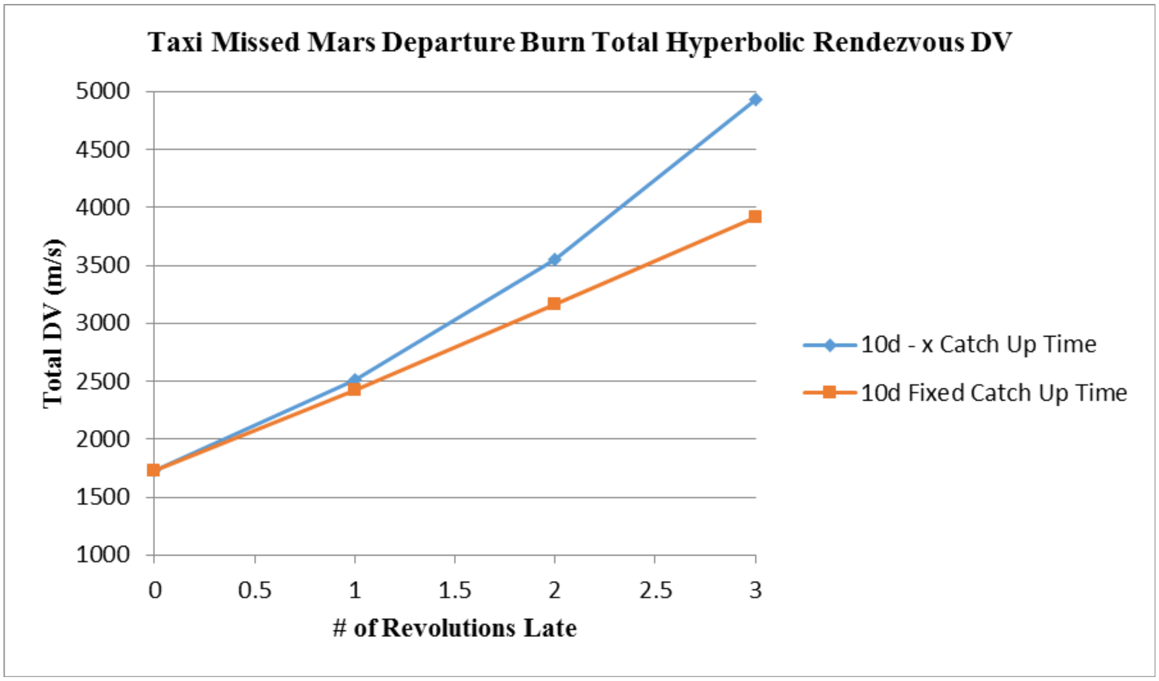

Figure 9. Total DV Cost for Missed Taxi Mars Departure Burns.

The 2 different sets of data represent different catch up philosophies. The assumption for both taxis is a 10 day lifetime. These 10 days would cover separation from the pre-deployed assets in Mars orbit to the rendezvous with the transit vehicle. In the "10d – x Catch Up Time" dataset, it is assumed that the additional revolutions in Mars orbit count against that 10 day lifetime. In the extreme case shown of leaving 3 revolutions late, the taxi now only has 7 days to catch up. The "10d Fixed Catch Up Time" dataset allows the taxi to use all 10 days to catch up, regardless of how late the taxi vehicle left. It makes sense that a resulting shorter catch up time would require a higher DV since the taxi has less time to recover the increase in range between the 2 vehicles. For a nominal departure of 1727 m/s, a missed burn would increase the required DV to at least 2426 m/s. Needless to say, accommodating this increase in DV would require a significant amount of additional propellant.

These results were based on the following set of initial conditions.

Table 9. Initial state of transit habitat for missed taxi departure scenario.

Parameter (Mars IAU)	Transit Vehicle	Parameter (Mars IAU)	Transit Vehicle
V_∞ (km/s)	4.0	Periapsis Altitude (km)	5,000
V_∞ Right Ascension (deg)	0	Eccentricity (-)	4.137
V_∞ Declination (deg)	0	Inclination (deg)	0
RAAN (deg)	0	RAAN (deg)	0
Periapsis Altitude (km)	5,000	AOP (deg)	-76
True Anomaly (deg)	0	True Anomaly (deg)	0

Much of the data produced in this study was motivated by support for the Mars Lite team[5]. Up to this point, the transit and taxi vehicle initial states were based on cases produced for the Mars Lite team. At this point in the analysis, it became clear a thorough understanding of hyperbolic rendezvous would be desired. This led to a new methodology of basing studies off of simplified reference states. These states are based off of a Mars International Astronomical Union (IAU) frame corresponding to the SPICE provided rotating, body fixed frame for Mars. The Mars IAU coordinate frame is an inertial built-in SPICE frame, defined by the Mars Mean Equator and IAU vector of J2000. The IAU vector at Mars is the point on the mean equator of Mars where the equator ascends through the Earth mean equator. This vector is the cross product of Earth mean North with Mars mean South[7]. Accordingly, the taxi vehicle's initial state was adjusted, as can be seen in Table 10.

Table 10. Initial state of taxi vehicle for missed taxi departure scenario.

Parameter (Mars IAU)	Taxi Vehicle
Period (days)	1.025
Periapsis Altitude (km)	250
Inclination (deg)	0
RAAN (deg)	180
Argument of Periapsis (deg)	93
True Anomaly (deg)	-45

One other change in the assumptions to point out is the orbit dimensions for the taxi were changed to a 1-sol Mars orbit (not 1 day) to better align with many other Mars architectures, such as NASA's DRA 5.0[6].

Impacts of Early Engine Cutoff

Another contingency that is examined for missions utilizing high thrust engines, is the impact of engines that do not complete burns, and do not reach the targeted velocity or energy state. The impact an early engine cutoff, or under speed, would have on hyperbolic rendezvous is forcing a later rendezvous time, or if the under speed is significant, preventing the taxi from ever reaching the transit vehicle. It is clear that the impacts of under speeds must be understood. For these cases, a correction burn is used to add the additional energy that is missed by the early engine cutoff. Correction burns occurring from 1-12 hours after engine cutoff are examined. 3 different % DV completions were examined with 3 different catch up times. The initial states of the transit and taxi vehicles are shown in the following tables.

Table 11. Transit vehicle's initial state for studying the impacts of early engine cutoff.

Parameter (Mars IAU)	Transit Vehicle	Parameter (Mars IAU)	Transit Vehicle
V_∞ (km/s)	3.75	Periapsis Altitude (km)	500
V_∞ Right Ascension (deg)	0	Eccentricity (deg)	2.279
V_∞ Declination (deg)	0	Inclination (deg)	0
RAAN (deg)	0	RAAN (deg)	0
Periapsis Altitude (km)	500	AOP (deg)	-116
True Anomaly (deg)	0	True Anomaly (deg)	0

These initial conditions follow the same methodology as the initial conditions shown in Table 9.

Table 12. Taxi vehicle's initial state for studying the impacts of early engine cutoff.

Parameter (Mars IAU)	Taxi Vehicle
Period (days)	1.025
Periapsis Altitude (km)	250
Inclination (deg)	0
RAAN (deg)	9
Argument of Periapsis (deg)	-126
True Anomaly (deg)	-43

The following figures show the results. For ease in differentiating the results, the figures show the results as an additional DV cost on the nominal trajectory. The nominal DV for each case is shown in each figure.

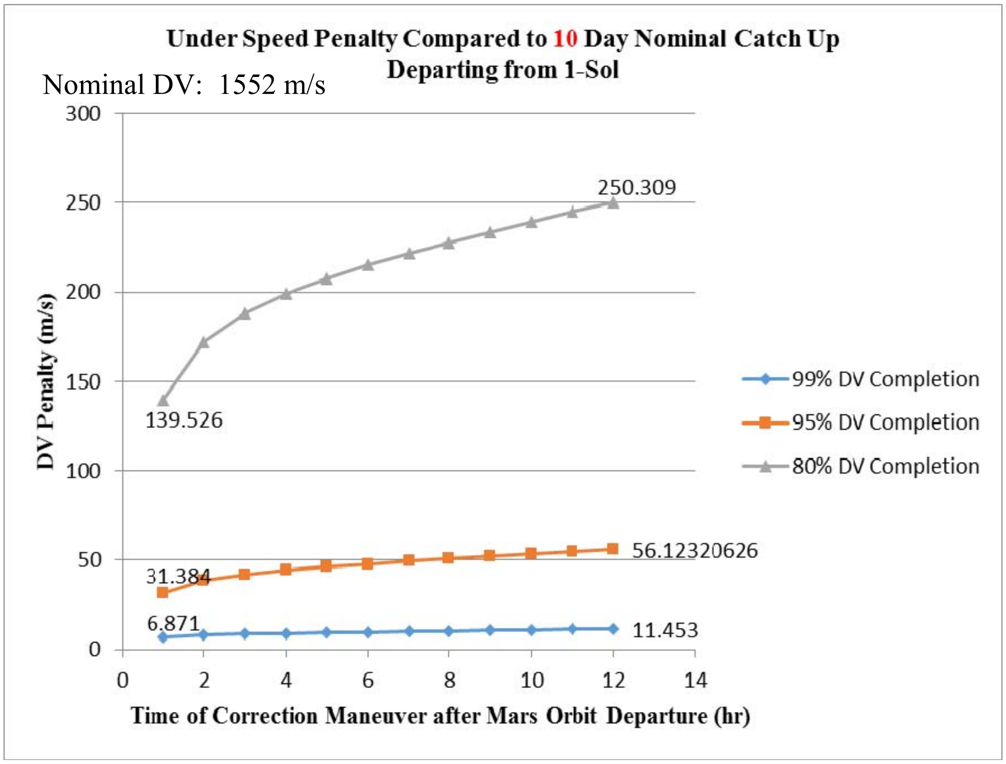

Figure 10. DV Penalty for various under speeds with a 10 day catch up time.

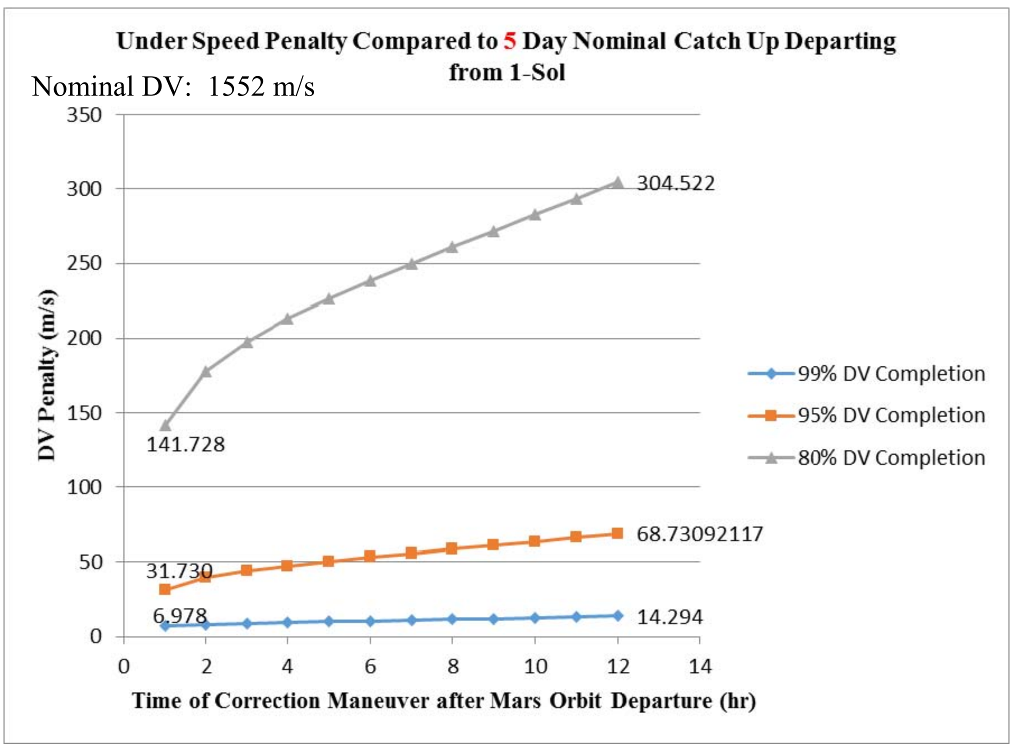

Figure 11. DV Penalty for various under speeds with a 5 day catch up time.

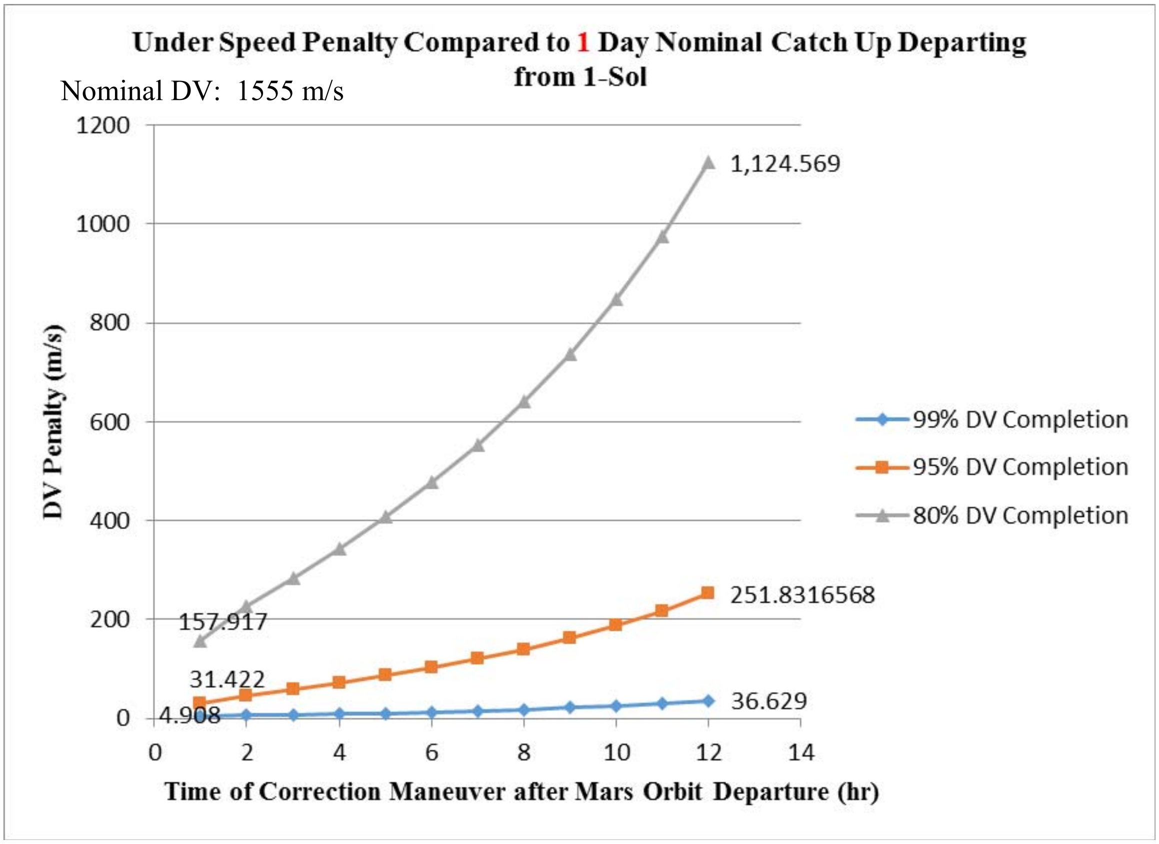

Figure 12. DV Penalty for various under speeds with a 1 day catch up time.

Figure 10, 11, and 12 show the impact an under speed can have on how much contingency propellant would need to be on board a vehicle attempting hyperbolic rendezvous. It is unknown what percentage of DV completions would need to be accounted for, but assuming most engines would perform at 95% or higher (excluding contingency and emergency scenarios) the amount of extra propellant required may not be prohibitive. Currently, NASA's Orion vehicle has the capability to down-mode from its primary Orbital Maneuvering System (OMS) to its auxiliary thrusters in less than an hour. If this capability is onboard the taxi vehicle, and a 95% DV completion with a correction burn 1 hour after the initial departure burn were to be protected for, only 31 m/s of DV would need to be provided (for the set of assumptions used here). For this case, where the nominal DV is 1,555 m/s, 31 m/s would only require a 2% margin.

Additional observations can be made about Figure 10, 10, and 11. These 3 cases departed from the same Mars parking orbit and targeted the same hyperbolic trajectory. For the 3 catch up times examined of 10, 5, and 1 day, the nominal DV's are 1,552, 1,552, and 1,555 m/s, respectively. These nominal DV's are all within 3 m/s of one another. This once again indicates the very small difference that exists in required DV for catch up times of 1 day and greater. These results all would all need to be taken into account when designing the active life time of the taxi vehicle and its sizing.

RISK MITIGATION STRATEGIES

In the previous section, several areas of risk inherit in a hyperbolic rendezvous were identified. There are many factors that come into consideration when quantifying the risk associated with different aspects of a mission and vehicle. Some of these factors, such as redundancy and the reliability of propulsion plumbing, navigation accuracy, etc., are beyond the scope of this paper. The design of the Mars orbit and maneuver operations can be used to mitigate many of the risks inherit in a hyperbolic rendezvous. This section suggests possible risk mitigation strategies.

Perhaps the greatest risk associated with a hyperbolic rendezvous is in the taxi vehicle missing its Mars departure burn. Figure 9 shows how significant Delta Velocity (DV) performance can be impacted by a missed Mars departure. Those results were not surprising given the extent of additional range between the vehicles once the transit habitat had its closest approach. Figure 13 expands on Figure 9 by including the impact of the taxi vehicle departing from Mars 1 revolution early.

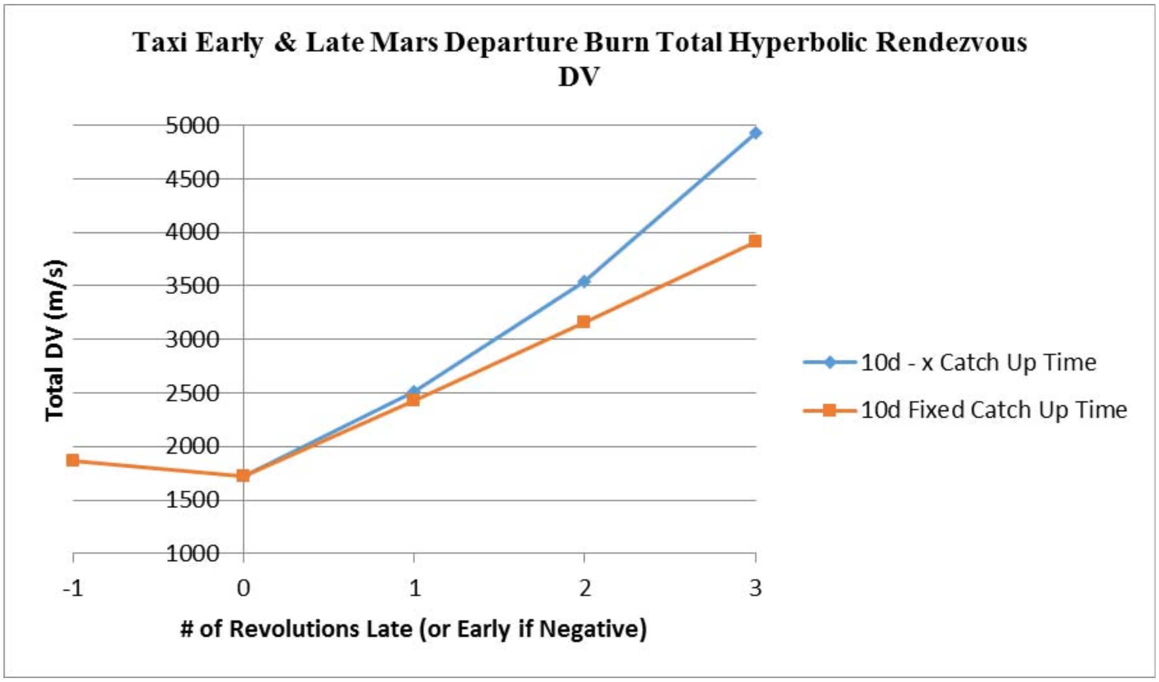

Figure 13. Total DV Cost for Early & Late Taxi Mars Departure Burns.

The 2 different sets of data represent different catch up philosophies. The assumption for both taxis is a 10 day lifetime. These 10 days would cover separation from the pre-deployed assets in Mars orbit to the rendezvous with the transit vehicle. In the "10d – x Catch Up Time" dataset, it is assumed that the additional revolutions in Mars orbit count against that 10 day lifetime. In the extreme case shown of leaving 3 revolutions late, the taxi now only has 7 days to catch up. The "10d Fixed Catch Up Time" dataset allows the taxi to use all 10 days to catch up, regardless of how late the taxi vehicle left. Figure 13 shows that the cost for departing Mars 1 revolution early is 1863 m/s, whereas the nominal case costs 1727 m/s. Departing 1 revolution early costs 136 m/s more than the nominal. 136 m/s is most likely a non-negligible amount of additional propellant mass that would need to be included in the taxi vehicle, however it still may result in an overall mission mass that is significantly less than bringing a larger vehicle that covers all exo-atmospheric portions of the mission as in many Mars architectures, such as NASA's Design Reference Architecture (DRA) 5.0. Additional investigation would need to be done to understand these impacts. If it turns out the extra propellant option leads to a lower mission mass than bringing all assets into Mars orbit, it may be feasible to have 2 opportunities to depart Mars and perform a hyperbolic rendezvous.

Another strategy investigated to provide more opportunities for the taxi to depart Mars may be to arrange the Mars parking orbit such that the taxi passes through periapsis at days -0.5, 0.5, etc., instead of what is shown in Figure 9 and 13. No trajectories have been generated to examine this strategy, but linearly interpolating the “10d Fixed Catch Up Time” data off of Figure 13 we have the following results:

Table 13. Total Hyperbolic Rendezvous DV Required for Departing 0.5 Days Before and After the Optimal Time.

Departure Revolution	Total DV (m/s)
-1.0	1,863
-0.5	1,795
0	1,727
0.5	2,077
1.0	2,426

Table 13 shows if 2 (or possibly more) opportunities are desired, the best vehicle sizing would be to keep the taxi’s departure time in whole revolution increments off of the optimal time. This would require sizing the vehicle with 1,863 m/s at departure, instead of what it would take to be able to depart 0.5 sol early or late, 2,077 m/s.

The effect of tweaking the orientation of the Mars parking orbit was also investigated to mitigate the impact an under speed would have on the required DV. There is an optimal angle between the periapses of the taxi and transit vehicles’ orbits. The following table shows the optimized Mars parking orbit orientation for different under speeds. These were found by forcing the initial burn to achieve only a certain percent of the required DV and correcting 1 hour after the initial burn completed.

Table 14. Optimized Mars parking orbit states for anticipated under speeds.

DV Completion (%)	Optimized Orbit State		
-	Inclination (deg)	RAAN (deg)	AOP (deg)
100	146	-159	185
95	146	-159	184
80	146	-159	182

In Table 14 RAAN is the Right Ascension of the Ascending Node, and AOP is the Argument of Periapsis. This table shows that optimizing the Mars parking orbit for an anticipated under speed leads to a reorientation of the AOP. The optimizer found rotating the AOP and essentially performing the Mars departure burn earlier would minimize the total DV required.

Before a reorientation of the Mars parking orbit can be considered, an understanding of what the performance looks like if the orbit was optimized for 80% completion, but 100% of the burn actually completes.

Table 15. Total hyperbolic rendezvous DV required for various under speeds and various orbit orientations.

DV Orbit is Optimized For (%)	Total DV Cost for Completing Various Percentages of the Initial Mars Departure Burn (m/s)		
-	100	95	80
100	2,364	2,396	2,506
95	2,379	2,390	Not Generated
80	2,415	Not Generated	2,462

The rows in Table 15 correspond to the taxi's orbit orientations given in Table 14. The columns show the total DV required to rendezvous from the different orbit orientations for different burn completion percentages. For instance, in the cell corresponding to 100% "DV Orbit is Optimized For" and 100% "Total DV Cost for Completing Various Percentages of the Initial Mars Departure Burn", or the 100-100 cell, the optimal rendezvous DV is shown. The 100-95 cell, where the total DV is 2396 m/s, corresponds to the DV required for a departure from the orbit optimized for 100% DV completion, but only 95% was achieved. The 95-100 cell, where the total DV is 2379 m/s, the vehicle departed from an orbit optimized for 95% DV completion, but 100% was actually achieved. This table shows how a balancing act can be performed to accommodate under speeds with less DV available. For example, if protection were to be provided for 80% burn completion, and the orbit optimized for 100% burn completion were used, 2506 m/s would need to be available. However, if an orbit optimized for 80% burn completion were used, only 2462 m/s needs to be provided. Even if the burn achieves 100% DV, and uses 2415 m/s, this is still less than 2506 m/s.

Another strategy to mitigate the risk involved in a Mars departure may be to raise the parking orbit's periapsis sometime before departure. For example, perhaps 9 sol prior to departure, the apoapsis may be raised such that the orbit has a period of 3 sol. This would serve 2 functions. First, if any issues were encountered during the apoapsis raise, there would be several days to troubleshoot before the required departure time. Also, by raising the apoapsis, the total DV required would be lowered somewhat by minimizing burn arcs and in turn minimizing gravity losses. However, a larger orbit will have impacts on the practicality of the other strategies discussed above. Which set of strategies ultimately lower the risk of hyperbolic rendezvous is beyond the scope of this paper.

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Title: Hyperbolic Rendezvous at Mars: Risk Assessments and Mitigation Strategies

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100 word abstract:

Given the current interest in the use of flyby trajectories for human Mars exploration, a key requirement is the capability to execute hyperbolic rendezvous. Hyperbolic rendezvous is used to transport crew from a Mars centered orbit, to a transiting Earth bound habitat that does a flyby. Representative cases are taken from future potential missions of this type, and a thorough sensitivity analysis of the hyperbolic rendezvous phase is performed. This includes early engine cut-off, missed burn times, and burn misalignment. A finite burn engine model is applied that assumes the hyperbolic rendezvous phase is done with at least two burns.

Extended abstract:

Hyperbolic rendezvous is a key requirement in the use of flyby trajectories for human Mars exploration. Flyby trajectories are of current interest due to the potential for decreasing overall mission mass, which likewise reduces mission cost. To conduct a mission with a flyby trajectory, hyperbolic rendezvous must be used to transport the crew from a captured Mars orbit to a transiting Earth bound habitat. Classical strategies that place a more massive vehicle, dedicated to the entire mission, into a captured Mars orbit require significantly more propellant. These classical strategies result in an overall increase in total mission mass. In contrast, hyperbolic rendezvous enables the use of smaller transportation-only service vehicles, known as taxi vehicles, to transfer the crew to pre-emplaced mission elements.

In this study, representative cases are taken from future potential missions of this type, and a thorough sensitivity analysis of the hyperbolic rendezvous phase is performed. Various parameters that effect hyperbolic rendezvous performance are assessed parametrically. Some of the parameters examined are hyperbolic excess velocity, periapsis altitude, and the transfer time for Mars orbiting assets to depart orbit and rendezvous with the Earth bound habitat. It is found that hyperbolic excess velocity is the primary factor effecting vehicle mass and propellant requirements. Periapsis altitudes were varied from 125 to 10,000 km. A maximum of 60 days is allowed for the Mars centered vehicle to depart Mars orbit and rendezvous with the Earth bound habitat. Figure i shows several cases demonstrating the effect hyperbolic excess velocity has on hyperbolic rendezvous performance. The catch-up time referenced in the legend is the amount of time allowed for the Mars centered vehicle to coast between Mars orbit departure and rendezvous with the Earth bound habitat. Figure i indicates that hyperbolic excess velocity has the primary impact on delta-velocity, and that hyperbolic periapsis altitude and catch-up time have a negligible impact.

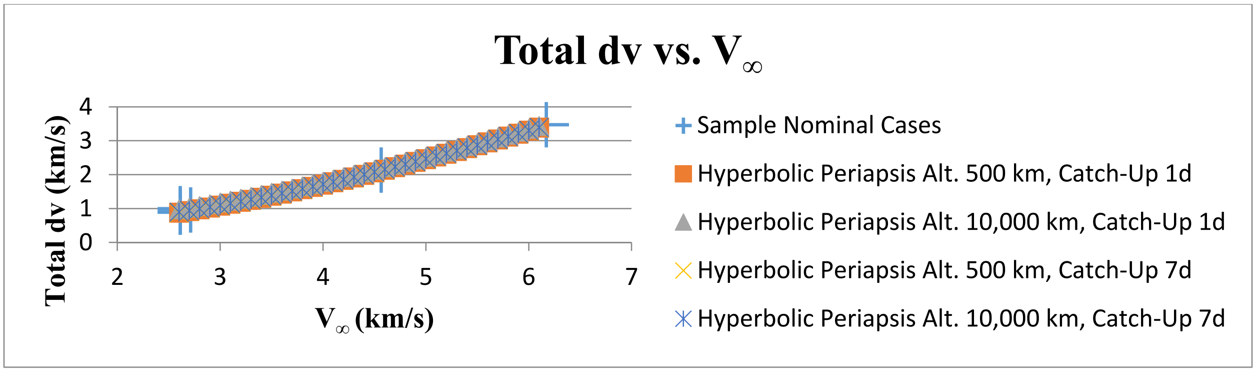

Figure i. Effect of Hyperbolic Elements on Rendezvous Performance

The primary tool used in this study is the Copernicus Trajectory Design and Optimization System. A finite burn engine model is applied that assumes the complete hyperbolic rendezvous phase is done with at least two burns. Results of the impact of various thrust-to-weight ratios compared to impulsive burns are shown. The taxi vehicle is the active vehicle. The transiting Earth bound habitat is the passive vehicle. It is assumed that there are no errors in the knowledge of both vehicles' current location and velocity.

Hyperbolic rendezvous is an orbital technique that has not been previously attempted. As such, this study also examines off-nominal mission scenarios. These scenarios include early engine cut-off, missed burn times, and burn misalignment. The findings outline risks associated with a hyperbolic rendezvous for a human Mars mission. Strategies to mitigate these risks are introduced. Some of these strategies include adjusting the timing of the nominal Mars departure burn, allowing for additional burns, and adjusting the nominal Mars centered parking orbit. Given the allowable performance margin that may be available for a human Mars mission, these strategies provide multiple contingencies to avert risk and safely perform a hyperbolic rendezvous mission. Upon nominal departure of the Mars centered orbit, a window on the order of minutes exists for the Mars departure burn to occur, provided the vehicle has 100 m/s of performance margin. Figure ii presents the sensitivity of the time of ignition for a hyperbolic excess velocity target of 5.055 km/s. Impulsive and finite burn cases are shown. The finite burn case assumes a thrust-to-weight ratio of 0.3. The legend also indicates how much higher the Earth bound habitat's periapsis is than the taxi vehicle. The Mars centered vehicle is in a 125 km x 3-sol orbit. 14 days is provided for the taxi vehicle to rendezvous with the Earth bound habitat.

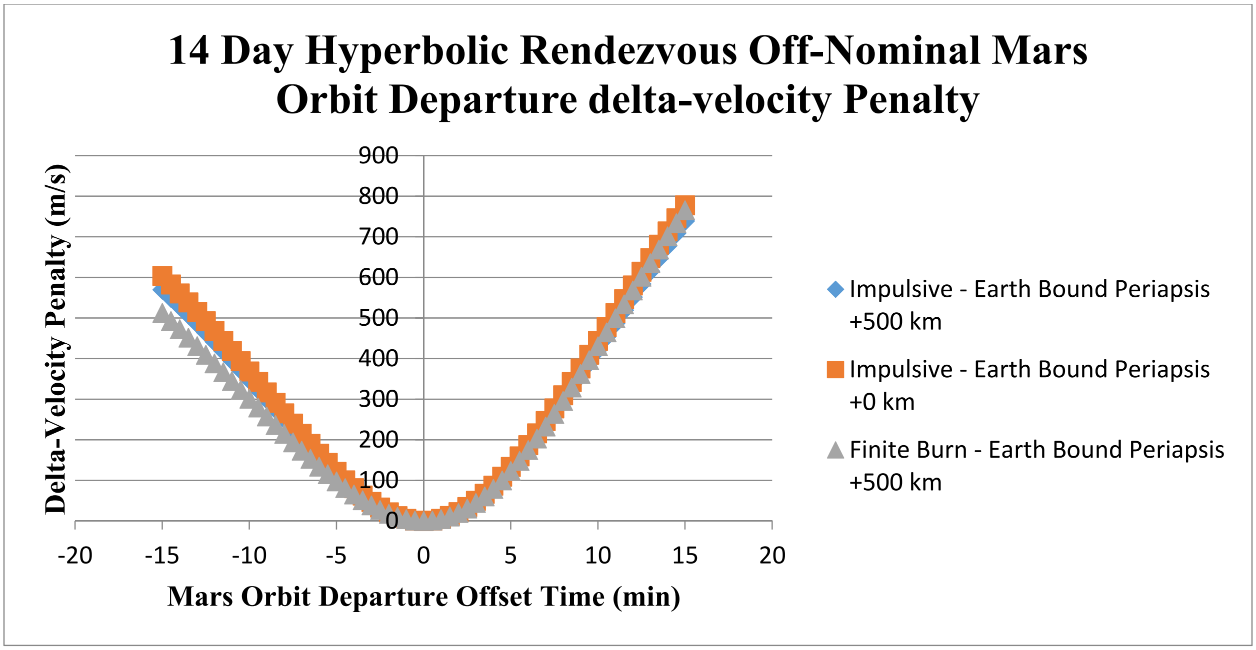

Figure ii. Mars Orbit Departure Burn Time of Ignition Sensitivity

One of the most concerning aspects of hyperbolic rendezvous is the notion that missing the nominal Mars departure burn can result in mission failure. This study finds that for a case when the optimal rendezvous delta-velocity is 1727 m/s, a departure 1 revolution early costs only 136 m/s more, which is a reasonable amount of margin to carry with the vehicle. This additional propellant margin provides 2 opportunities to perform hyperbolic rendezvous. Adjustments to the Mars centered orbit's line of apsides can reduce the impact of underperforming engines as well. Adjusting the line of apsides will prevent a truly optimal burn from taking place, but will reduce the amount of additional propellant that needs to be accounted for when an engine underperforms. Additional burns can also be added to offset the impact of underperforming engines so hyperbolic rendezvous can still be performed on time.