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Influence of Interplanetary Trajectory Selection on Mars Atmospheric Entry Velocity

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Many current manned Mars mission studies are using low lift-to-drag ratio (*L/D*) vehicles to aerobrake at both Mars and Earth. The use of these low *L/D* vehicles could limit the allowable velocity at the atmospheric interface. This paper will demonstrate that if entry velocity constraints are incorporated into the interplanetary analysis of aerobraking Mars missions, many opportunities can be achieved for a small increase in initial mass in low-Earth orbit (IMLEO). These opportunities result from varying the initial launch date and the encounter dates and possibly using a powered Venus swingby on either the inbound or outbound transfer. This paper demonstrates this technique by using three atmospheric entry velocity ranges at Mars arrival (6.0–8.5, 6.4–8.1, and 7.2–7.3 km/s), unconstrained Mars entry velocities, and an Earth return entry velocity below 14 km/s. The results indicate that, by carefully selecting the interplanetary trajectory, an optimum IMLEO mission can be found for even highly restrictive entry velocity missions in practically all of the 15 yr studied.

Introduction

IN 1989, President George Bush tasked this nation to proceed with the human exploration of the solar system by returning to the moon and then continuing on to Mars. An enhancing technology for this manned Mars mission is an aerobraking maneuver; aerobraking is a method in which a spacecraft uses atmospheric drag rather than an onboard propulsion system to capture into orbit. Low lift-to-drag ratio (*L/D*) Mars aerobrake vehicles would allow for greater design commonality with current lunar mission vehicles. Additionally, studies have shown that lower *L/D* configurations generally result in lower aerobrake vehicle mass (and thus potentially lower mission cost).[1] Also, since lower *L/D* vehicles are more restrictive than higher *L/D* vehicles (in terms of flyable corridor width),[2] this study will examine only Mars missions that use low *L/D* configurations ($L/D < 0.5$).

This aerobraking mission analysis investigates the amount that the vehicle's initial mass in low-Earth orbit (IMLEO) must increase above the minimum mass mission to meet several specified atmospheric entry velocity ranges at Mars. This study also determines the effects and feasibility of using various interplanetary trajectory options to increase the number of launch opportunities for manned Mars aerobraking missions having constrained atmospheric entry velocities at Mars arrival. Additionally, the Earth entry velocity is constrained below 14 km/s throughout this analysis.

Background

Currently, there is general agreement that typical Mars atmospheric entry velocities will be between 6 and 10 km/s for the types of mission trajectories analyzed in this study. However, the allowable Mars entry velocity range could decrease once heating and deceleration limitations are included in the atmospheric trajectory analysis of low *L/D* vehicles. To assess the impact of just such a constraint on the Mars entry velocity, three candidate ranges were selected for this analysis. These atmospheric entry velocity ranges, to be targeted upon Mars arrival, are 6.0–8.5, 6.4–8.1, and 7.2–7.3 km/s.

For this study, the Earth return payload and Mars lander mass assumptions were taken from a paper by Braun et al.,[3] in which the mass of an artificial gravity vehicle with a chemical propulsion system is described. Also, the stages were assumed to have engines with 480 s specific impulse (Isp), as well as structural and tankage mass that is 10% of that stages' propellant mass. The aerobrake mass is approximated as 15% of the aerobraked mass (not including the aerobrake), as has been previously used.[4]

A 1–2 yr total mission time limit was used throughout this analysis. These missions begin from a 500 km, circular parking orbit at Earth. At Mars, a 1 Sol (24.6-h period) parking orbit with a 500 km periapse altitude is used throughout the 60 day stay. The Mars and Earth atmospheric interfaces are assumed to be at altitudes of 300 and 125 km, respectively. A minimum Venus swingby radius of 6800 km was used to avoid atmospheric encounter. These assumptions for the mission are summarized in Table 1.

Approach

For this analysis of direct, inbound, and outbound Venus swingby Mars mission trajectories occurring between 2010 and 2025, a three-dimensional patched conic simulation technique is

Table 1 Vehicle and mission parameters

Vehicle	
Mars excursion module mass, kg	76,000
Earth return mass, kg	61,000
Structural mass, kg	10% of propellant mass
Engine specific impulse (Isp), s	480
Aerobrake mass, kg	15% of mass aerobraked
Mission	
Periapsis altitude, km (for all parking orbits)	500
Parking orbit eccentricities	
Initial Earth orbit	0.000
Mars parking orbit	0.807
Final Earth orbit	0.838
Minimum Venus swingby periapsis radius, km	6800
Atmospheric interface altitude	
Mars, km	300
Earth, km	125

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used. The Earth and Mars departure maneuvers are considered impulsive and assumed to be tangential. Initially, the minimum IMLEO, unconstrained entry velocity mission's encounter dates were determined using a combination of grid searches and numerical optimization. Next, the linear quadratic optimization routine (VF02AD)[5] determined the encounter dates that minimized IMLEO while meeting the specified entry velocity ranges. Since previous studies have indicated that optimized propulsive maneuvers at the periapsis of the gravity assist trajectory can favorably alter IMLEO and swingby date,[6] powered Venus swingbys [with non-tangential, impulsive, and minimized velocity increment (ΔV) maneuvers] were allowed so that a greater number of encounter dates could be included in this analysis. Additionally, Mars was assumed to have a uniform mass distribution; that is, orbital precession effects were not taken into account during the stay time.

Figures 1a and 1b illustrate the technique used in this analysis to achieve the desired Mars entry velocity ranges, while minimizing IMLEO, for an outbound Venus swingby transfer departing Earth on December 14, 2010. Figure 1a shows the encounter dates (and thus planetary positions) for the unconstrained Mars entry velocity mission having the minimum IMLEO. Note that the Mars entry velocity is 8.76 km/s in this case. Figure 1b indicates the effect that changing the Mars arrival, Venus swingby, and Earth arrival dates has on the interplanetary transfer geometry. By carefully selecting these encounter dates, a mission can be found that meets the preset Mars entry velocity range and minimizes IMLEO (for this example, the Mars entry velocity was lowered to 7.28 km/s, within the 7.2–7.3 km/s range). This approach is used throughout this analysis.

Results and Discussion

In this section, the departure opportunities for the various Mars entry velocity ranges will be discussed first. These opportunity plots show periods of departure for the various transfer types used (the length of these periods is shown above the blocks in the figures). These plots do not illustrate traditional launch windows, instead they indicate when that transfer type is available and meets

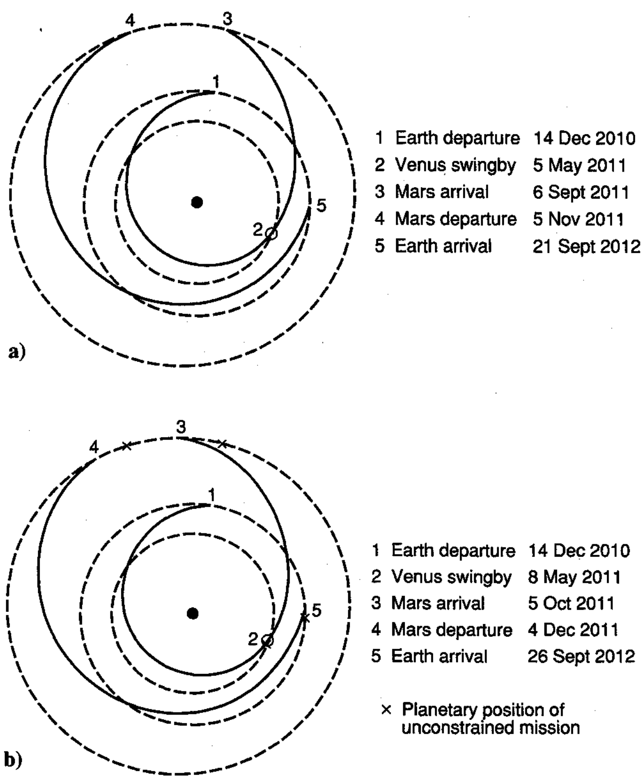

Fig. 1 Earth-Mars transfer with outbound venus swingby: a) unconstrained Mars entry velocity (8.76 km/s), and b) constrained Earth entry velocity (7.28 km/s).

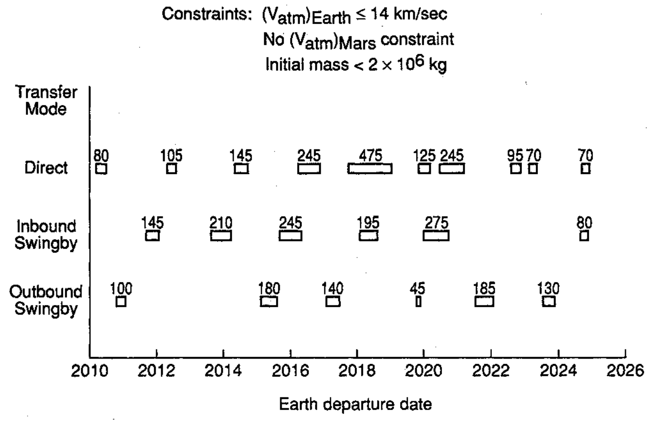

Fig. 2 Opportunities for unconstrained Mars atmospheric entry velocity aerobraking missions.

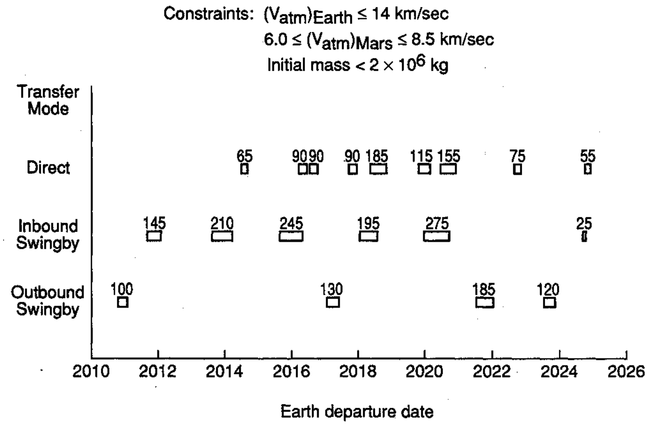

Fig. 3 Opportunities for missions with Mars entry velocity between 6.0 and 8.5 km/s.

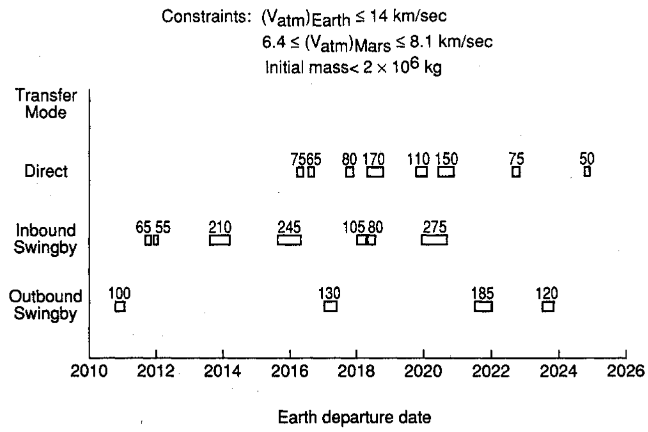

Fig. 4 Opportunities for missions with Mars entry velocity between 6.4 and 8.1 km/s.

the IMLEO, total trip time, and any entry velocity constraints applicable to that plot. Second, the increase of IMLEO required to meet the entry velocity constraint ranges for each transfer type is discussed. Finally, a compilation of the IMLEO for all transfer types over the entire 2010–25 time period for each entry velocity range is included.

When compared with the unconstrained entry velocity missions (Fig. 2), missions with Mars entry velocities between 6.0 and 8.5 km/s (Fig. 3) have either a fewer number or reduced length of opportunities. Comparison of these figures shows that only four

Table 2 Average initial LEO mass increase above unconstrained Mars entry velocity missions

Departure Opportunity		Mars entry velocity range								
		6.0–8.5 km/s × 10^6 kg			6.4–8.1 km/s × 10^6 kg			7.2–7.3 km/s × 10^6 kg		
Year	Type[a]	Low	High	Average	Low	High	Average	Low	High	Average
2010	O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.77	0.03
2017	O	0.00	2.42	0.09	0.00	0.92	0.08	0.00	2.07	0.22
2021	O	0.00	0.21	0.01	0.00	3.09	0.03	0.05	3.86	0.22
2023	O	0.00	1.83	0.03	0.00	7.84	0.13	N/A[b]	N/A	N/A
2011	I	0.00	0.10	0.02	0.00	1.19	0.25	0.00	7.30	0.36
2013	I	0.00	0.00	0.00	0.00	0.02	0.01	0.00	0.40	0.14
2016	I	0.00	0.56	0.05	0.00	0.95	0.07	0.00	4.05	0.14
2018	I	0.00	0.00	0.00	0.00	0.61	0.09	0.00	3.42	0.27
2020	I	0.00	0.00	0.00	0.00	0.02	0.09	0.00	0.40	0.07
2024	I	0.00	0.62	0.32	0.19	4.25	0.67	N/A	N/A	N/A
2014	D	0.00	0.79	0.06	N/A	N/A	N/A	N/A	N/A	N/A
2016	D	0.00	0.05	0.00	0.00	0.05	0.00	0.00	0.80	0.30
2018	D	0.00	0.25	0.00	0.00	0.23	0.02	0.00	0.05	0.01
2020	D	0.00	0.17	0.01	0.00	0.47	0.04	0.00	0.64	0.14
2022	D	0.00	0.13	0.01	0.00	0.23	0.02	0.00	0.35	0.04
2024	D	0.00	0.02	0.00	0.00	0.05	0.01	0.00	0.12	0.04

[a]O = outbound swingby; I = inbound swingby; D = direct mission.
[b]N/A = no missions available that meet all of the velocity criteria.

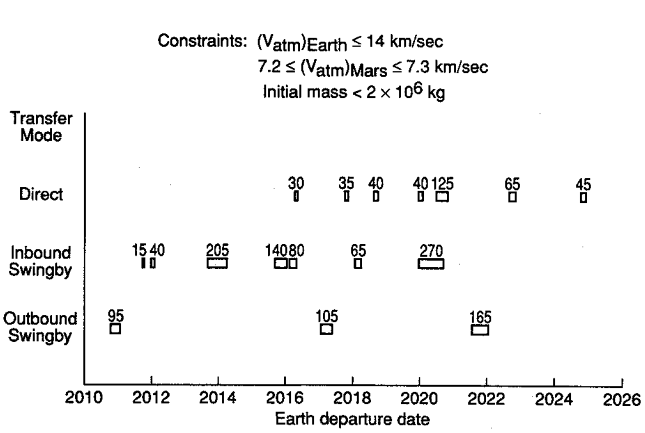

Fig. 5 Opportunities for missions with Mars entry velocity between 7.2 and 7.3 km/s.

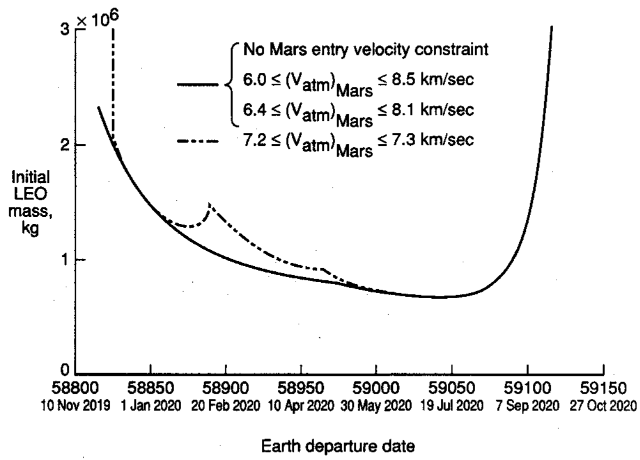

Fig. 6 IMLEO of the inbound Venus swingby missions within the Mars entry velocity ranges in 2020.

outbound swingby and six direct mission opportunities remain, but all of the inbound swingby mission opportunities are intact (although one is significantly reduced). For the most part, the resilience of these missions is caused by the inbound swingby transfers providing the most control over the Earth entry velocity. That is, since two encounter dates (Venus swingby and Earth arrival dates) occur on the inbound, or Earth arrival, leg of the mission, the interplanetary trajectory can be more easily altered to control the arrival conditions at Earth once the Mars entry velocity restrictions have been met. Even with the reduced mission possibilities, opportunities for these entry velocity missions still exist during each of the 15 yr studied.

The opportunities for Mars missions with entry velocities in the 6.4–8.1 km/s range (Fig. 4) are only slightly different than for the previously restricted Mars entry velocity range (Fig. 3). Only two opportunities are lost (one direct and the smallest inbound swingby opportunity) and the lengths of the remaining opportunities are reduced by only a small amount. This small change indicates that there is little difference (in terms of departure opportunities) in requiring that the entry velocity be in the range that is almost 1 km/s smaller. Even with these slight differences, there are still departure possibilities in each year from 2010–25.

Figure 5 shows possible Mars missions with 7.2–7.3 km/s entry velocities. Even this most restrictive entry velocity case has opportunities to depart in 14 of the 15 yr examined (2023 is the one exception). The inbound swingby missions have most of the original unconstrained opportunities remaining, whereas the outbound swingby and direct mission opportunities are distributed throughout 2010–25. As with the other entry velocity ranges, the direct missions' departure periods have been greatly reduced by requiring the use of these most restrictive entry velocity constraints. (Compare Figs. 2 and 5.) This fact can be attributed to the direct missions having the fewest number of encounter dates to control and thus limiting the effect that changing the available dates has on entry velocity. Since more dates are available to control, the swingby missions have retained most of their original departure period, even with the extreme entry velocity restrictions; subsequently, several inbound swingby mission opportunities remain mostly unchanged.

The average increase in IMLEO required of the unconstrained Mars entry velocity missions to meet each of the constrained Mars entry velocity missions is compiled in Table 2. The four outbound Venus swingby mission opportunities have little cost associated with satisfying the requirements of constrained Mars entry velocity missions. These outbound swingby opportunities have missions with minimum initial LEO masses around 0.61 million kg. There are six inbound Venus swingby mission opportunities in which missions having Mars entry velocities between 6.0 and 8.5 km/s are possible; five opportunities have missions with Mars entry velocities in the 6.4–8.1 and 7.2–7.3 km/s ranges and initial LEO mass below 2 million kg. Table 2 shows that average IMLEO increases for most of the Venus swingby, constrained Mars entry velocity missions are less than 0.24 million kg above the unconstrained Mars entry velocity missions. The inbound swingby mission opportunity in 2020 (see Fig. 6) has some of the lowest average IMLEO increase above the unconstrained entry velocity

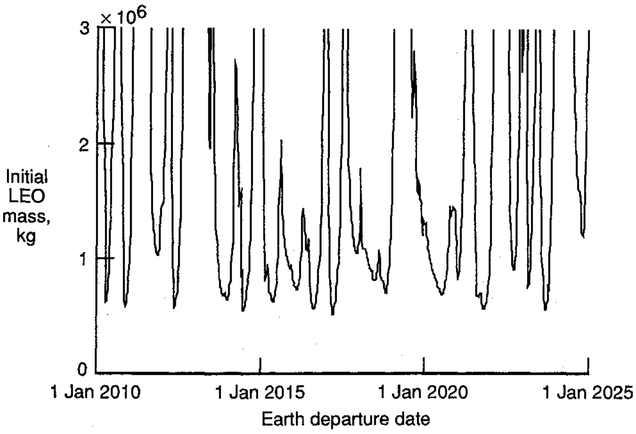

Fig. 7 Lowest IMLEO for unconstrained Mars entry velocity missions.

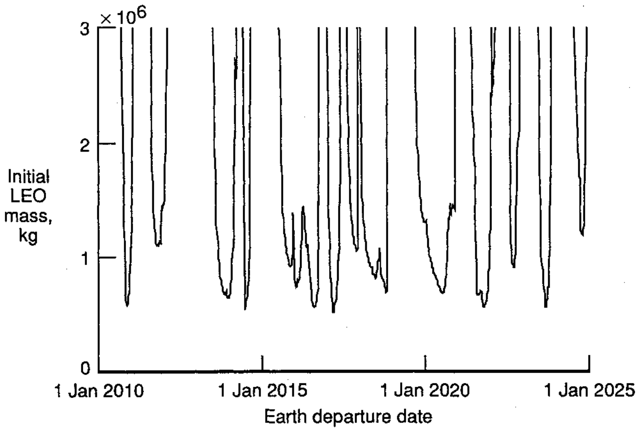

Fig. 8 Lowest IMLEO for missions with Mars entry velocity between 6.0 and 8.5 km/s.

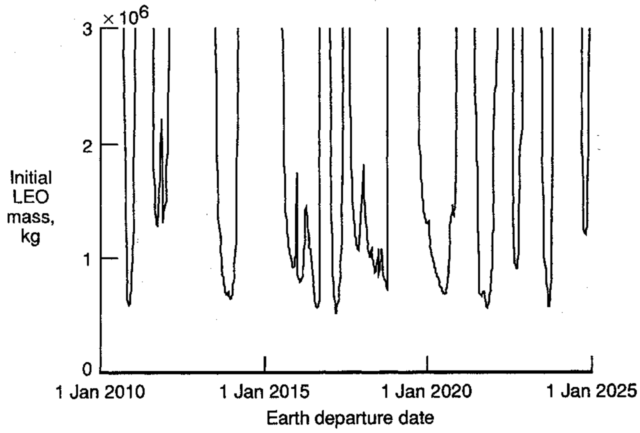

Fig. 9 Lowest IMLEO for missions with Mars entry velocity between 6.4 and 8.1 km/s.

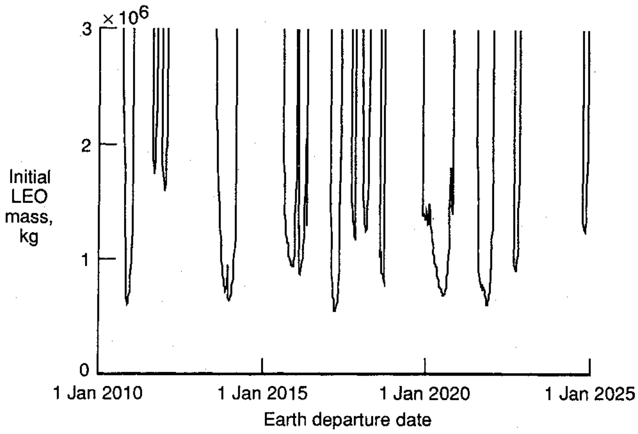

Fig. 10 Lowest IMLEO for missions with Mars entry velocity beween 7.2 and 7.3 km/s.

mission needed to attain the various Mars entry velocity constraint ranges. Little initial mass increase is needed for the constrained Mars entry velocity, direct missions during the time in which they are possible. Table 2 indicates that, on average, less than a 0.1 million kg IMLEO increase above the unconstrained Mars entry velocity missions is required to complete most of the direct, constrained Mars entry velocity missions.

The minimum initial LEO mass for the unconstrained and three constrained Mars entry velocity missions (regardless of transfer type) is compiled in Figs. 7–10 for each departure date in the 2010–25 time period. These figures reiterate the results discussed earlier. The unconstrained Mars entry velocity missions (Fig. 7) cover nearly the entire 15-yr period with every year offering a launch opportunity having initial mass well below 2 million kg (with quite a few less than 1 million kg). More gaps appear in the plot of the 6.0–8.5 km/s Mars entry velocity missions (Fig. 8); nevertheless, many of these opportunities' initial masses are still well below 2 million kg (a substantial number below 1 million kg). As the entry velocity range is reduced further (Fig. 9), the gaps become more pronounced and the curves start to shift up slightly; however, there are still plenty of missions with IMLEO below 1 and 2 million kg. The gaps and upward shift of the curves is more apparent for the 7.2–7.3 km/s range (Fig. 10), but a substantial number of missions having IMLEO below 2 million kg remain (with a significant number below 1 million kg).

In summary, the initial mass of missions with Mars entry velocities in the 6.0–8.5 and 6.4–8.1 km/s ranges are very similar to the unconstrained Mars entry velocity missions. Even the most restricted entry velocity mission (Earth entry velocity less than 14 km/s and Mars entry velocity between 7.2 and 7.3 km/s) has a significant number of missions with initial mass below 2 million kg in the 2010–25 time period. Even though the cost for this most constrained entry velocity case can be potentially high, these missions are still attainable during 14 of the 15 yr studied. Furthermore, several of these missions have initial LEO vehicle mass below 1 million kg.

Conclusions

Vehicle design studies have shown that lower lift-to-drag ratio (*L/D*) aerobraking vehicles have less mass (and thus potentially lower cost) than higher *L/D* vehicles. This analysis examines the effects and feasibility of constraining the Mars atmospheric entry velocity of missions that use low *L/D* aerobrake vehicles. Three different Martian atmospheric entry velocity ranges were assumed for this study: 6.0–8.5, 6.4–8.1, and 7.2–7.3 km/s, whereas, the Earth entry velocity was restricted below 14 km/s throughout this analysis. Each entry velocity range examined in this study could be attained throughout the 2010–25 time frame.

Departure opportunities are available for the unconstrained, 6.0–8.5 and 6.4–8.1 km/s Mars entry velocity missions in every year from 2010–25. The most restricted entry velocity mission (Mars entry velocity between 7.2–7.3 km/sec) still has departures possible in all but one of the 15 yr analyzed. Therefore, by carefully selecting the interplanetary trajectory, an optimum initial LEO mass mission (below 2 million kg) can be found for even highly restrictive entry velocity missions in practically all of the 15 yr studied.

The cost of the missions with entry velocities between 6.0–8.5 km/s is the lowest of all of the constrained Mars entry velocity missions. The 6.4–8.1 km/s entry velocity missions also require very low IMLEO increases (on average, less than 0.09 million kg). The most constrained entry velocity mission has an averaged increase of less than 0.14 million kg for a majority of the missions. Thus, the net effect of the entry velocity restrictions on aerobraking missions is slight in terms of increased initial LEO mass (less than a 10% increase).

From the interplanetary trajectory analysis, there appears to be little difference, on average, in restricting the Mars entry velocity to be between 6.4–8.1 and 6.0–8.5 km/s. Also, the 7.2–7.3 km/s entry velocity range has a substantial number of departure opportunities in the 2010–25 time frame. Therefore, from a mission opportunity viewpoint, even the 7.2–7.3 km/s entry velocity range can be considered feasible for manned Mars missions, with a small increase in initial mass.

Even though specific entry velocity ranges were used in this analysis, the general conclusions would remain the same if different ranges were targeted. That is, a larger range of Mars entry velocities provides more departure opportunities, whereas a smaller range has less opportunities and generally costs more (in terms of initial LEO mass). However, a significant number of opportunities to depart will remain for Mars entry velocity ranges greater than 0.1 km/s (e.g., 6.3–6.4 or 7.9–8.6 km/s). Finally, the capability of the swingby missions to meet the entry velocity constraints must be attributed in part to the increased freedom that the powered swingby option provides. The powered swingby allows more swingby dates to be considered than an unpowered swingby would permit; therefore, better control can be exercised over the interplanetary trajectory, and thus, the arrival conditions at Mars and Earth.

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