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Influence of Interplanetary Trajectory Selection on Earth Atmospheric Entry Velocity of Mars Missions

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Many current manned Mars mission studies are using low lift-to-drag ratio vehicles to aerobrake at both Mars and Earth. This paper will demonstrate that if entry velocity constraints are incorporated into the interplanetary analysis of aerobraking Mars missions, more opportunities can be achieved for only a small increase in initial mass in low-Earth orbit (IMLEO). These additional 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 not only presents unconstrained entry velocity missions but also includes results for entry velocities below 12.5 and 14 km/s on Earth return and between 6.0-8.5 km/s at Mars arrival. The results indicate that, regardless of the Mars entry velocity range selected, an Earth entry velocity below 14 km/s is easily attainable for a minimal IMLEO increase. Although there are fewer 12.5 km/s Earth entry velocity missions possible, both Mars entry velocity constraint cases have over 50% of their missions requiring a negligible IMLEO increase.

Introduction

RECENT studies of manned Mars missions have used aerobraking at Mars and Earth to reduce the propulsive requirements for these vehicles. This mission-enhancing technique uses atmospheric drag rather than an onboard propulsion system to capture into orbit. Both high and low lift-to-drag ratio (L/D) aerobrake vehicles have been suggested for use during Mars missions. However, to allow some design commonality with currently proposed lunar return vehicles, only low lift-to-drag ratio aerobrake vehicles ($L/D < 0.5$) will be considered in this analysis. Additionally, studies have shown that lower L/D configurations generally result in lower aerobrake vehicle mass (and thus lower mission cost).[1] 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 various atmospheric entry velocity limitations at Earth. 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 and Earth arrival. This paper will concentrate on Earth atmospheric entry velocity considerations; however, one Mars atmospheric entry velocity range is included to determine its impact on missions with an Earth entry velocity limitation.

Background

There has been much discussion about what entry velocity limitations should be used for Earth return from Mars missions. Braun and Powell[2] concluded that, from a guidance standpoint, Earth entries above 14 km/s would eliminate low L/D aerobrake vehicle concepts from consideration. Tauber and Palmer[3] concurred that no guidance corridor exists for low L/D aerobrake vehicles with entry velocities above 14 km/s; furthermore, they noted that an upper limit of 14 km/s can be used when taking into account mission abort considerations. Walberg[4] stated that, above 14 km/s, the aerothermodynamic environment around the aerobrake is dominated by radiative heating, whereas below 14 km/s convective and radiative heating are comparable. In other words, the higher entry velocity yields a more complex aerothermodynamic environment and a higher heat rate. Therefore, to permit lower L/D aerobraking vehicle concepts, an upper limit of 14 km/s was selected for analysis as one of the Earth entry velocity limits.

Another entry velocity restriction selected for study is 12.5 km/s at Earth. The rationale for this selection is due more to aerothermodynamic considerations than guidance issues. At lower velocities, uncertainties in the ionization chemical kinetics models (used to analyze flows about aerobraking vehicles) are less significant due to the lower percentage of radiative heating contributing to the overall heating of the aerobrake. Thus, the aerothermodynamic environment can be more accurately analyzed at lower entry velocities using current models and techniques. Since the Apollo moon missions entered around 11.1 km/s,[5] the 12.5 km/s constraint allows an entry environment similar to those missions (for which aerothermal data exist) and provides a reasonable upper limit for vehicles returning from Mars.

Typically, Mars atmospheric entry velocities will be between 6 and 10 km/s for the types of mission trajectories analyzed in this study. However, this range could be limited for low L/D aerobrake vehicles due to heating and deceleration limits. Thus, a 6.0–8.5 km/s Mars entry velocity range will be included in this analysis to simulate such a possible limitation.

The spacecraft used in this study is a chemically propelled, artificial gravity vehicle presented by Braun et al.[6] for a 1–2 yr roundtrip Mars mission. Specifically, the terminal (or Earth return) payload and the mass left at Mars (lander) were used from this reference. (See Table 1.) The engines have a specific impulse (Isp) of 480 s, and structure and tankage for propulsion stages are 10% of the propellant required for that stage. As used in previous studies, the mass of these low L/D aerobrakes is approximated to be 15% of the entry mass, excluding the aerobrake.[7]

The mission simulation begins from a circular, 500-km altitude parking orbit at Earth. Upon arrival at Mars, the vehicle is placed into an orbit with a one Martian day, or 24.6h, period (a 1 Sol orbit) and a 500 km periapsis altitude. The spacecraft remains in Mars

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Table 1 Vehicle and mission parameters

Vehicle	
Earth return 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)	
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

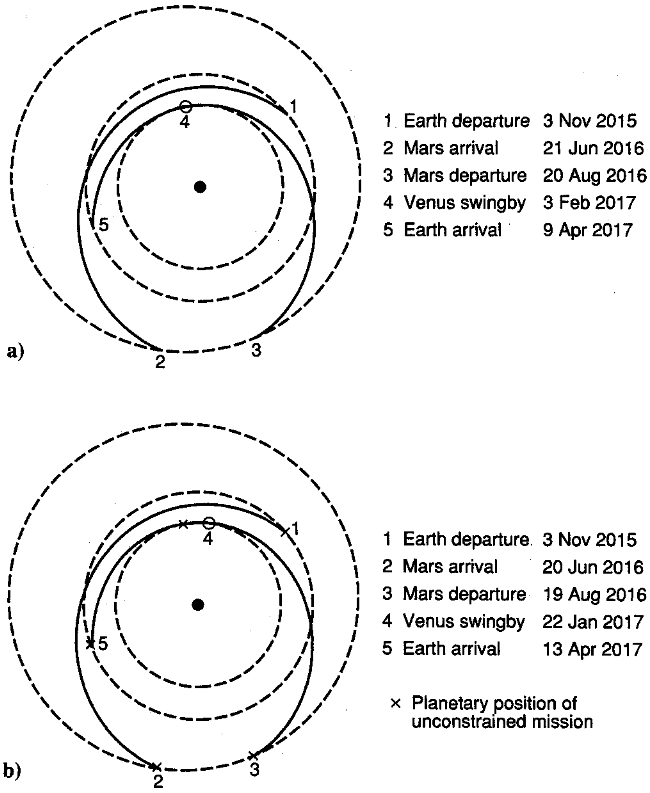

Fig. 1 Earth-Mars transfer with inbound Venus swingby: a) unconstrained Earth entry velocity (15.2 km/s), and b) constrained Earth entry velocity (14.0 km/s).

orbit for 60 days. The total mission time was limited to be between 1 and 2 yr. For these aerobraking missions, the Martian atmospheric interface occurs at a 300 km altitude, whereas at Earth this interface is at a 125-km altitude. These mission parameters are summarized in Table 1.

Approach

This study analyzed direct, inbound, and outbound Venus swingby Earth-Mars trajectories in the 2010–25 time frame. An initial, broad grid search, encompassing all possible encounter dates of the mission being studied, was employed to find potential minimum IMLEO regions for unconstrained entry velocity missions. After further grid refinement, a linear quadratic optimization routine (VF02AD)[8] was used to determine date sequences that minimized the initial mass of this mission. Then, for the constrained entry velocity missions, this optimization routine was used to determine the encounter dates that meet the entry velocity constraint ranges while minimizing the required IMLEO of the mission's vehicle.

An example of the technique used to meet the atmospheric entry velocity constraints while minimizing IMLEO is shown in Figs. 1a and 1b for the November 3, 2015, Earth departure date. As shown in Fig. 1a, the initial encounter dates (and hence planetary positions) for the minimum IMLEO, unconstrained entry velocity mission were determined; for this example, the Earth entry velocity is 15.2 km/s. A couple of the dates for this inbound Venus swingby mission were then changed (Earth arrival and Venus swingby dates in this case, but the Mars arrival date could also be changed when needed) so that the entry velocities could meet the constraints (see Fig. 1b); now, the Earth entry velocity is 14 km/s, below one of the prescribed limits. Thus, by shifting the encounter dates (planetary positions), the geometry of the interplanetary transfer was altered enough to influence the entry velocities into the established limits.

The interplanetary trajectories were simulated using a three-dimensional patched conic approach. The swingby trajectories minimized the velocity increment (ΔV) needed when using the periapse altitude (620 km minimum to avoid atmospheric interaction) and angle of burn required to properly complete the gravity assist maneuver. The Venus swingbys were allowed to be powered since previous studies have shown that propulsive maneuvers at the periapsis of the inbound hyperbola can have a significant impact on swingby date and IMLEO.[9] All propulsive maneuvers determined in this analysis are considered impulsive. Also, only tangential propulsive maneuvers at periapsis are used for the departure burns at Mars and Earth. Furthermore, the effects due to orbital precession over the 60-day stay time at Mars are ignored; disregarding these effects is the same as assuming a spherical, uniform mass distribution planet.

Results and Discussion

This section will begin with an analysis of the departure opportunities for missions having no velocity limit, a 14 and a 12.5 km/s

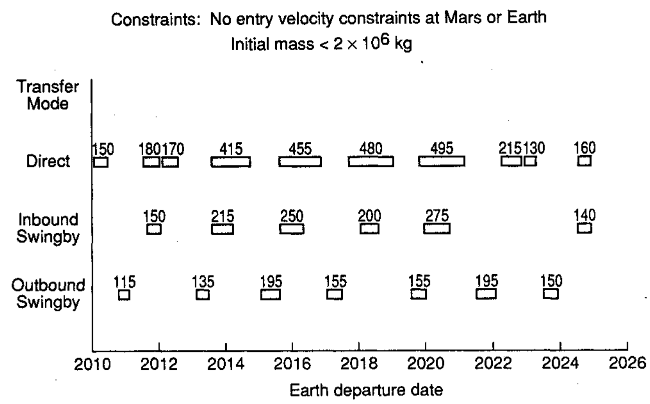

Fig. 2 Opportunities for unconstrained atmospheric entry velocity aerobraking missions.

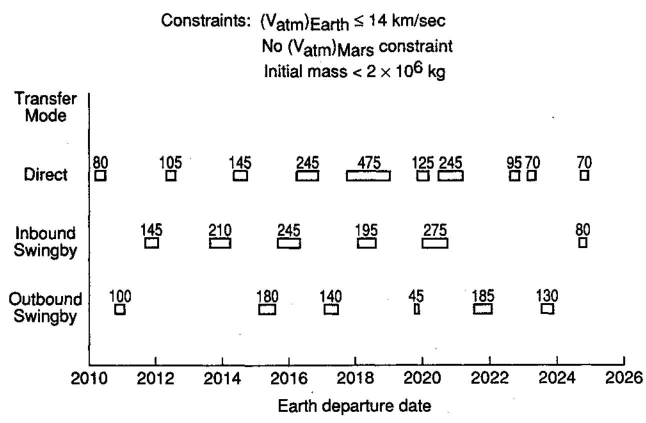

Fig. 3 Opportunities for unconstrained Mars, constrained Earth (≤14 km/s) entry velocity missions.

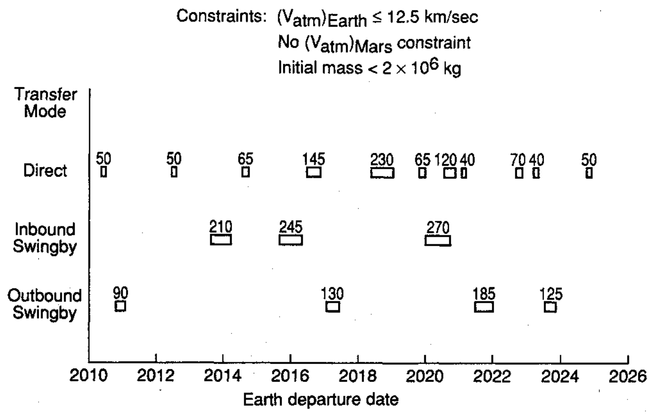

Fig. 4 Opportunities for unconstrained Mars, constrained Earth (≤12.5 km/s) entry velocity missions.

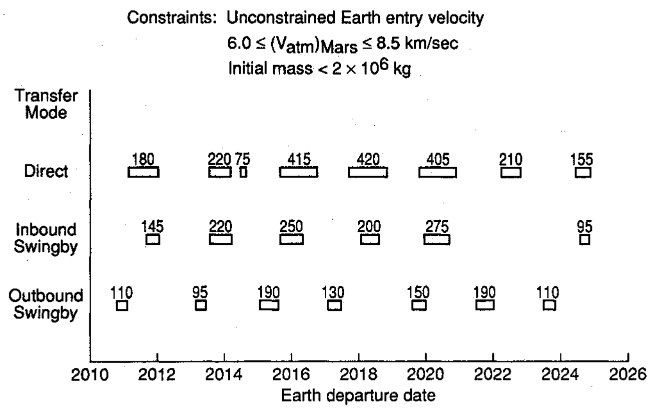

Fig. 5 Opportunities for constrained Mars, unconstrained Earth entry velocity missions.

upper limit on the Earth atmospheric entry velocity. Additionally, this analysis will include an unconstrained and 6.0–8.5 km/s entry velocity range at Mars; the constraint at Mars will also be applied throughout this study to guarantee that changing the Earth entry velocity does not overly affect the missions with restricted entry velocity at Mars. The 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 the IMLEO, total trip time, and any entry velocity constraints applicable to that plot. In this analysis, the largest initial mass considered feasible is 2 million kg. Next, the increase of IMLEO required to meet the entry velocity limits will be assessed for each transfer type. Finally, a compilation of the IMLEO for all transfer types over the entire 2010–25 time period for each entry velocity constraint is included.

A comparison of mission opportunities for only the unconstrained and constrained Earth entry velocity, excluding the Mars entry velocity range, is included to initiate this section. Upon comparing the unconstrained entry velocity missions (Fig. 2) with the missions having an Earth entry velocity below 14 km/s (Fig. 3), all of the inbound swingby and one less outbound swingby and direct mission opportunities remain (the direct opportunity in 2020 has split). That is, six inbound, six outbound Venus swingby, and nine direct mission opportunities are left after constraining the Earth entry velocity to below 14 km/s. Comparison of the unconstrained (Fig. 2) and less than 12.5 km/s (Fig. 4) Earth entry velocity missions shows that many more opportunities are reduced or lost than for the less severe entry velocity restriction. For the 12.5 km/s missions, nine direct, three inbound, and four outbound Venus swingby mission opportunities remain (similar to before, the direct opportunity in 2020 is split into three parts). Most of the opportunities have been reduced in length for both Earth entry velocity limits, most notably the direct mission opportunities. Surprisingly, the inbound Venus swingby missions lost three opportunities in the 12.5-km/s Earth entry velocity cases even though these missions have the most control over the shape of the Earth return trajectory; the opportunities that do remain are only reduced in length by five days. However, there is at least one type of mission opportunity for each of the 15 yr examined, even for the missions with the 12.5 km/s limit at Earth; thus, every year still has possible departure dates.

For the missions that meet the 6.0–8.5 km/s Mars entry velocity range, the inbound Venus swingby mission opportunities change the least when comparing the unconstrained opportunities (Fig. 5) with the missions with Earth entry velocity below 14 km/s (Fig. 6). As before, the inbound Venus swingby missions constrained to 12.5 km/s at Earth entry (see Fig. 7) lose three opportunities; however, the three remaining inbound swingby mission opportunities are relatively unchanged in length compared with the unconstrained Earth entry velocity missions. As before, the direct missions are greatly reduced as the Earth entry is forced to occur at lower velocities; this inability of the direct missions to affect entry velocity can be attributed to these missions having the fewest number of encounter dates to control.

The next issue to address is the cost associated with modifying the unconstrained Earth entry velocity missions to meet the two Earth entry velocity constraints. Table 2 shows the average increase of various Mars and Earth constrained entry velocity missions above the unconstrained Earth entry velocity mission. That is, each Earth and Mars entry velocity constraint case is compared with the associated unconstrained Earth entry velocity case (e.g., constrained Earth and Mars mission is compared with unconstrained Earth, constrained Mars mission). The averaging period shown in the table is the time period over which IMLEO comparisons are made; to allow a more complete comparison, these averaging periods include, but are not limited to, the entire departure

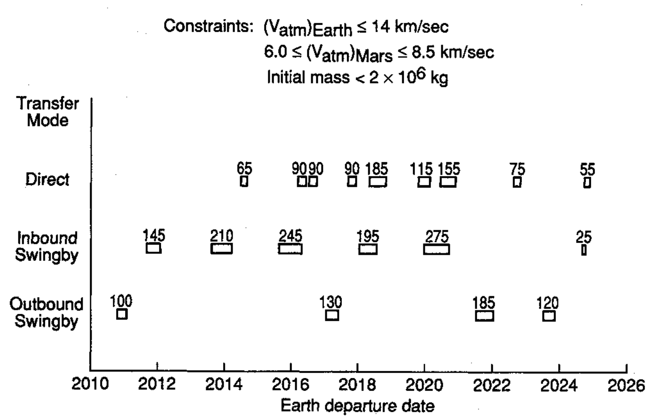

Fig. 6 Opportunities for constrained Mars, constrained Earth (≤14 km/s) entry velocity missions.

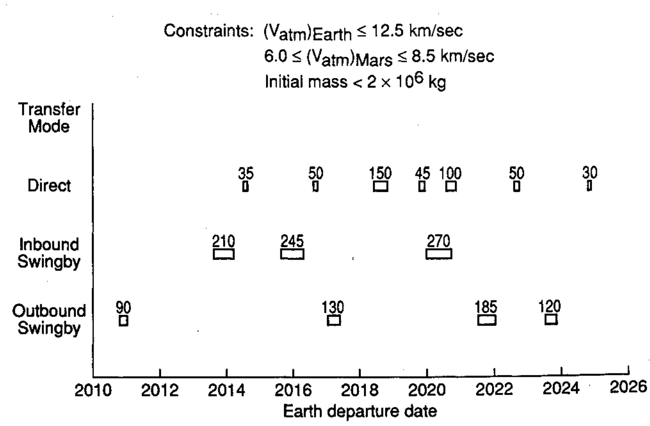

Fig. 7 Opportunities for constrained Mars, constrained Earth (≤12.5 km/s) entry velocity missions.

period of the opportunity listed. When comparing these averages, the length of the averaging period for the missions being compared should be noted. To assist in assessing the impact of including Earth entry velocity constraints, Table 3 is included to indicate the periods of time in which the IMLEO increase is below a certain limit. In Table 3, the three IMLEO increases studied equate to a 5, 2.5, and 0.5% increase for a 2 million-kg vehicle; that is, these amounts of increase are notable but still small.

In Table 2, there appears to be little cost required of the Venus swingby, unconstrained Mars entry velocity missions to meet the 14-km/s Earth entry velocity constraint (nominally around 0.10 and 0.07 million kg, or less, for most inbound and outbound Venus swingby opportunities, respectively). The direct missions show a slightly larger initial mass increase required for the unconstrained missions to meet the 14-km/s Earth entry velocity constraint (0.22 million kg or less in a majority of the cases). For the missions having entry velocities below 12.5 km/s, the average IMLEO penalty is higher, as expected, but several opportunities average less than a 0.15 million-kg increase. Again, the direct missions had the most difficulty in achieving the 12.5 km/s constraint.

Table 2 also includes the constrained Mars missions. From this section of the table, a comparison of the average increase for the constrained and unconstrained Earth entry velocity missions is useful. Again, note that the difference in the number of days in the averaging period can be significant. Most of the missions having Earth entry below 14 km/s differ from the unconstrained Earth entry velocity averages by less than 0.05 million kg. Even though the missions with Earth entry velocity constrained below 12.5 km/s have fewer opportunities, the majority of the remaining opportunities have IMLEO increases less than 0.06 million kg greater than the unconstrained Earth, constrained Mars entry velocity mission. Note that the averaging periods for the direct missions with Earth entry velocity less than 12.5 km/s have substantially fewer days than the other missions studied; however, the swingby missions

Table 2 Average increase in IMLEO above unconstrained Earth entry velocity missions

Departure Opportunity		Unconstrained Mars entry velocity, Mkg								6.0 ≤ Vatm[a] at Mars ≤ 8.5 km/s, Mkg							
		Vatm at Earth ≤ 14 km/s				Vatm at Earth ≤ 12.5 km/s				Vatm at Earth ≤ 14 km/s				Vatm at Earth ≤ 12.5 km/s			
Year	Type[b]	Low	High	Ave	Ave period, days	Low	High	Ave	Ave period, days	Low	High	Ave	Ave period, days	Low	High	Ave	Ave period, days
2010	O	0.00	0.82	0.09	110	0.02	0.83	0.18	105	0.00	0.82	0.09	110	0.04	1.03	0.23	105
2017	O	0.00	0.72	0.06	155	0.00	1.32	0.13	140	0.00	0.00	0.00	140	0.00	0.45	0.06	140
2021	O	0.00	0.48	0.04	215	0.00	0.93	0.14	205	0.00	0.48	0.04	215	0.00	0.66	0.18	210
2023	O	0.00	1.05	0.12	140	0.00	1.04	0.14	135	0.00	0.02	0.00	125	0.00	0.09	0.01	125
2011	I	0.03	0.11	0.05	165	N/A[c]	N/A	N/A	N/A	0.03	0.11	0.05	165	N/A	N/A	N/A	N/A
2013	I	0.00	0.00	0.00	230	0.00	0.00	0.00	230	0.00	0.00	0.00	230	0.00	0.00	0.00	230
2016	I	0.00	0.02	0.00	265	0.00	0.22	0.07	265	0.00	0.16	0.01	260	0.00	0.58	0.09	255
2018	I	0.07	0.25	0.09	200	N/A	N/A	N/A	N/A	0.07	0.25	0.09	200	N/A	N/A	N/A	N/A
2020	I	0.00	0.02	0.00	295	0.00	0.58	0.02	280	0.00	0.02	0.00	295	0.00	0.58	0.02	280
2024	I	0.48	0.82	0.60	130	N/A	N/A	N/A	N/A	0.51	0.91	0.71	70	N/A	N/A	N/A	N/A
2014	D	0.00	1.10	0.22	145	0.00	0.18	0.22	65	0.00	0.00	0.00	65	0.00	0.00	0.00	35
2016	D	0.00	1.15	0.25	250	0.00	1.18	0.25	145	0.00	1.14	0.28	190	0.00	0.10	0.01	50
2018	D	0.00	0.93	0.14	475	0.00	0.83	0.14	225	0.00	0.37	0.06	275	0.13	0.83	0.32	145
2020	D	0.00	0.82	0.11	395	0.00	1.10	0.11	250	0.00	0.50	0.07	280	0.00	0.59	0.15	145
2022	D	0.00	0.53	0.06	95	0.00	0.53	0.06	70	0.00	0.13	0.01	75	0.00	0.03	0.00	50
2024	D	0.20	0.76	0.31	70	0.20	0.69	0.31	50	0.17	0.39	0.23	55	0.17	0.22	0.19	30

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

Table 3 Periods for certain IMLEO increases above unconstrained Earth entry velocity missions

Departure Opportunity		Unconstrained Mars entry velocity, days								6.0 < Vatm[a] at Mars < 8.5 km/s, days							
		Vatm at Earth < 14 km/s				Vatm at Earth < 12.5 km/s				Vatm at Earth < 14 km/s				Vatm at Earth < 12.5 km/s			
		Period with increase			Total	Period with increase			Total	Period with increase			Total	Period with increase			Total
Year	Type[b]	<0.10 Mkg	<0.05 Mkg	<0.01 Mkg	period, days	<0.10 Mkg	<0.05 Mkg	<0.01 Mkg	period, days	<0.10 Mkg	<0.05 Mkg	<0.01 Mkg	period, days	<0.10 Mkg	<0.05 Mkg	<0.01 Mkg	period, days
2010	O	85	80	70	110	60	15	0	105	85	80	70	110	55	5	0	105
2017	O	130	125	115	155	110	105	105	140	140	140	140	140	110	105	105	140
2021	O	185	170	155	215	125	40	5	205	185	170	150	215	30	10	5	210
2023	O	105	105	90	140	100	90	85	135	125	125	120	125	125	110	90	125
2011	I	160	95	0	165	N/A[c]	N/A	N/A	N/A	160	95	0	165	N/A	N/A	N/A	N/A
2013	I	230	230	230	230	230	230	230	230	230	230	230	230	230	230	230	230
2016	I	265	265	225	265	175	165	155	265	255	250	200	260	155	135	85	255
2018	I	155	0	0	200	N/A	N/A	N/A	N/A	155	0	0	200	N/A	N/A	N/A	N/A
2020	I	295	295	290	295	265	255	245	280	295	295	290	295	265	255	245	280
2024	I	0	0	0	130	N/A	N/A	N/A	N/A	0	0	0	70	N/A	N/A	N/A	N/A
2014	D	95	95	90	145	60	60	60	65	65	65	65	65	35	35	35	35
2016	D	120	115	110	250	80	80	75	145	85	80	75	190	45	45	40	50
2018	D	275	240	160	475	55	50	45	225	215	180	90	275	0	0	0	145
2020	D	265	235	190	395	115	105	80	250	205	175	135	280	70	60	35	145
2022	D	75	70	65	95	60	55	50	70	70	65	60	75	50	50	40	50
2024	D	0	0	0	70	0	0	0	50	0	0	0	55	0	0	0	30
TOTAL		2440	2120	1790	3335	1435	1250	1135	2165	2270	1950	1625	2750	1170	1040	910	1800
Percentage		73	64	54	—	66	58	52	—	83	71	59	—	65	58	51	—

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

have approximately the same number of days in their averaging periods.

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.

A more complete understanding of the impact that including the Earth entry velocity constraints has on all of the mission opportunities can be obtained using Table 3. This table contains the time periods that require 0.10, 0.05, and 0.01 million-kg increases, or less, above the unconstrained Earth entry velocity mission's IMLEO. As seen in Table 3, both the constrained and unconstrained Mars entry velocity, inbound Venus swingby missions have the most days with the lowest IMLEO increase, when the missions are available, for either Earth entry velocity case. As

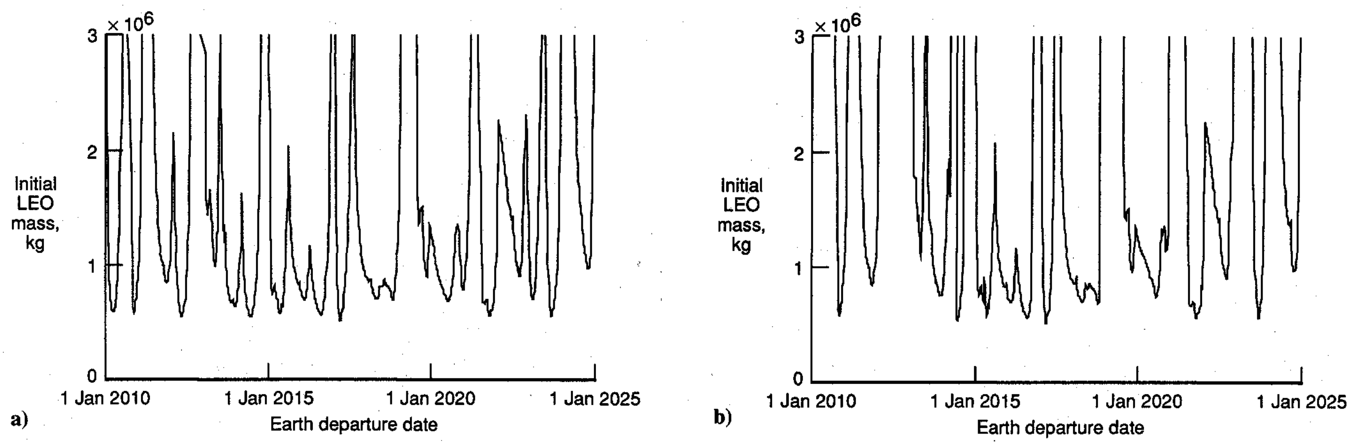

Fig. 8 Lowest IMLEO for unconstrained Earth entry velocity missions: a) unconstrained Mars entry velocity, and b) constrained Mars entry velocity.

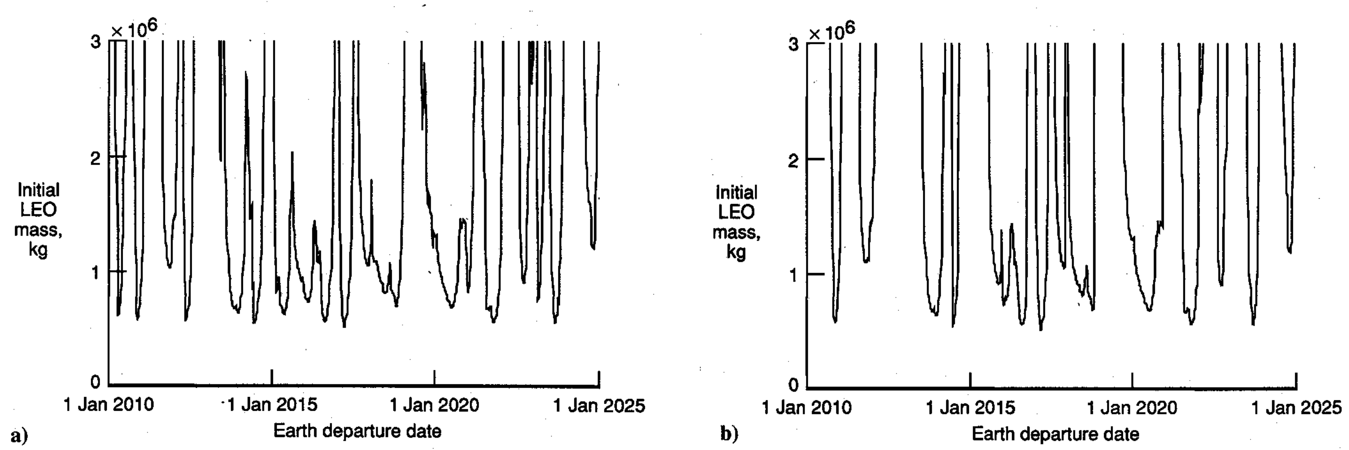

Fig. 9 Lowest IMLEO for missions with Earth entry velocity below 14 km/s: a) unconstrained Mars entry velocity, and b) constrained Mars entry velocity.

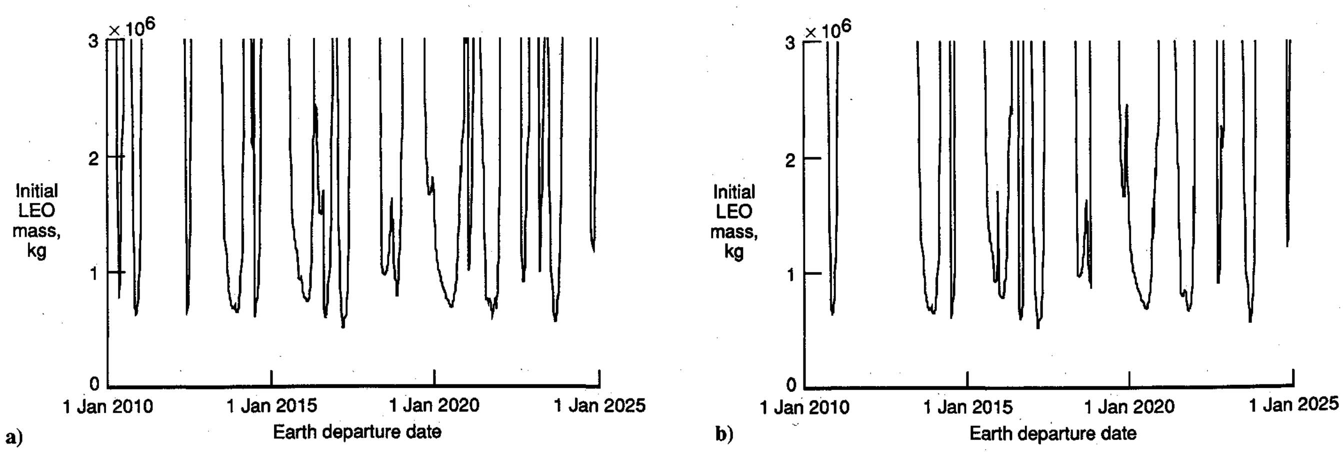

Fig. 10 Lowest IMLEO for missions with Earth entry velocity below 12.5 km/s: a) unconstrained Mars entry velocity, and b) constrained Mars entry velocity.

noted earlier, the direct missions have the most difficulty in meeting the Earth entry velocity constraints. Also, a few opportunities have no missions with IMLEO increases below 0.10 million kg.

However, the last two rows of Table 3 indicate that the overall IMLEO increase for the entire 15-yr period studied is quite favorable. In each Earth entry velocity case, over 50% of the missions required a negligible increase in IMLEO; note that the total period for the 12.5 km/s Earth entry velocity missions is much less than the 14-km/s missions. In terms of percentage, there is no difference between the constrained and unconstrained Mars, 12.5 km/s Earth entry velocity missions. However, the constrained Mars, 14-km/s Earth entry velocity missions have a higher percentage of lower IMLEO increases than the unconstrained Mars entry velocity missions, with over 80% of the constrained Mars entry velocity missions having IMLEO increases less than 0.10 million kg.

A further indicator of the required IMLEO for the constrained and unconstrained Mars and Earth entry velocity missions (regardless of transfer type) can be found in Figs. 8-10 for each departure date in the 2010-25 time period. These figures reiterate the results discussed earlier. The unconstrained Earth entry velocity missions (Fig. 8) 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 plots (Fig. 9) when the Earth entry velocity is constrained to be below 14 km/s. However, many of these opportunities' initial masses are below 2 million kg. Although many of the opportunities have been reduced in length, the 12.5 km/s Earth entry velocity missions (Fig. 10) still have a significant number of missions with IMLEO below 2 million kg (with an appreciable number below 1 million kg).

The unconstrained (Figs. 8a, 9a, and 10a) and constrained (Figs. 8b, 9b, and 10b) Mars entry velocity missions show a similar trend. As the Earth entry velocity ceiling is lowered, the opportunities are reduced in length and the IMLEO curves begin to shift upward, indicating that some cost is involved in including these constraints. However, these plots also illustrate that many missions with IMLEO below 1 million kg exist for even the 12.5 km/s Earth entry velocity missions.

Conclusions

Vehicle design studies have shown that lower lift-to-drag ratio (*L/D*) aerobraking vehicles have less mass (and thus lower cost) than higher *L/D* vehicles. This analysis examined the effects and feasibility of constraining the atmospheric entry velocities at Mars and Earth for manned Mars missions using low *L/D* aerobrake vehicles. Several Earth entry velocity limitations were studied (unconstrained, 14, and 12.5 km/s); two Mars entry velocity conditions were also included (unconstrained and 6.0–8.5 km/s range).

As the Earth entry velocity restriction is lowered, fewer and shorter opportunities are available. However, each of the 15 yr studied have missions with Earth entry velocity below 14 km/s, whereas missions with less than 12.5 km/s Earth entry and constrained Mars entry velocity are possible in 14 of the 15 yr. The direct missions typically had higher IMLEO increases than the Venus swingby missions. As expected, the 12.5-km/s limitation required a greater increase in the unconstrained mission's IMLEO than did the 14-km/s constraint. Nearly 60% of the constrained Mars, 14 km/s Earth entry velocity missions studied required a negligible IMLEO increase above the constrained Mars, unconstrained Earth entry velocity missions, whereas over 80% of those missions needed less than a 0.10 million-kg increase. Although there are constrained Mars entry velocity missions possible when the 12.5-km/s Earth entry limit is imposed, both Mars entry velocity constraint cases have over 50% of their missions requiring a negligible IMLEO increase. Therefore, by carefully selecting the interplanetary trajectory, a mission requiring only a small IMLEO increase can be found for even highly restrictive entry velocity missions in practically all of the 15 yr studied. Finally, regardless of the Mars entry velocity range selected, an Earth entry velocity below 14 km/s is easily attainable for a minimal IMLEO increase.

Even though the mission in this study returned 61,000 kg to Earth, the use of a much less massive Earth return capsule (ERC) would only increase the number of missions with low Earth entry velocity and IMLEO below 2 million kg. Additionally, the penalty to the mission's vehicle to meet the 14- and 12.5-km/s Earth entry velocity constraints should be lower than the current results if an ERC were used. Finally, the trends shown in the present study for lowering the Earth entry velocity would still be valid even with the use of an ERC.

References

[1]Walberg, G. D., "A Survey of Aeroassisted Orbit Transfer," *Journal of Spacecraft and Rockets*, Vol. 22, No. 1, 1985, pp. 3–18.

[2]Braun, R. D., and Powell, R. W., "Earth Aerobraking Strategies for Manned Return from Mars," AIAA Paper 91-2873, Aug. 1991.

[3]Tauber, M., and Palmer, G., "Earth Atmospheric Entry Studies for Manned Mars Missions," AIAA Paper 90-1699, June 1990.

[4]Walberg, G. D., "A Review of Aerobraking for Mars Missions," International Astronautical Federation, IAF Paper 88-196, Oct. 1988.

[5]Berry, R. L., "Launch Window and Translunar, Lunar Orbit, and Transearth Trajectory Planning and Control for the Apollo 11 Lunar Landing Mission," AIAA Paper 70-24, Jan. 1970.

[6]Braun, R. D., Powell, R. W., and Hartung, L. C., "Effect of Interplanetary Trajectory Options on a Manned Mars Aerobrake Configuration," NASA TP-3019, Aug. 1990.

[7]Freeman, D. C., Jr., Powell, R. W., and Braun, R. D., "Manned Mars Aerobrake Vehicle Design Issues," International Astronautical Federation, IAF Paper 90-197, Oct. 1990.

[8]Chang, J. Y., "Recursive Quadratic Programming with Best Feasible Point," Ph.D. Dissertation, Dept. of Aerospace Engineering and Engineering Mechanics, Univ. of Texas at Austin, Austin, TX, May 1989.

[9]Striepe, S. A., and Braun, R. D., "Effects of A Venus Swingby Periapsis Burn During an Earth-Mars Trajectory," *Journal of the Astronautical Sciences*, Vol. 39, No. 3, 1991, pp. 299–312.

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