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Rapid Interplanetary Round Trips at Moderate Energy*

James R. Wertz
Microcosm, Inc.
401 Coral Circle, El Segundo, CA 90245
jwertz@smad.com

ABSTRACT

We define a new class of "rapid round trip" interplanetary missions for which the principal characteristic is a total mission duration that is 1 or more years shorter than the traditional round trip using Hohmann transfers. Round trip missions using Hohmann transfers to near-Earth asteroids or other nearby interplanetary objects may require many years. (For example, 8 years for a round trip to a Near-Earth Asteroid at 1.1 AU.) Consequently, rapid round trips are the only practical means for human space travel to these objects.

The Hohmann round trip mission to Mars typically requires about 2.7 years. Rapid round trips to Mars can be as short as 5 months in total mission duration, but these trips require delta V's 5 times or more greater than for Hohmann round trips. This paper explores rapid round trip missions that are intermediate in terms of both total mission duration and total delta V required. These are significantly faster and take a greater delta V than Hohmann round trips, but are not as fast and use less delta V than the very rapid missions. For example, an intermediate round trip mission to Mars can have a total duration of 14 to 15 months, stay on the surface of Mars of 2 to 3 months, and a total applied delta V of around 14 km/sec if direct entry is used.

INTRODUCTION*

Nearly all of the interplanetary round trip analysis to date has focused on minimum energy round trips or small deviations from minimum energy. (See, for example, the excellent work by Aldrin [1985], Friedlander, et al. [1986], Hoffman and Soldner [1985], Hoffman, McAdams, and Niehoff [1989], Polsgrove and Adams [2002], and Young [1988].) Certainly this is a practical approach given the high cost of rocket travel. The basic result of this work has been round trips to Mars on the order of 970 days (2.7 years) or longer in total duration. Increasing the delta V applied to the trip did very little to change the total round trip time.

The Microcosm IR&D study, begun in September, 1999, has focused instead on what it would take to dramatically reduce the total round trip time. Doing so requires a much higher delta V, but reduces the operations and support cost, particularly for human missions. Reduced trip times may be important for many types of human missions and is critical for any extensive human space travel. Mars is unlikely to become a popular tourist destination with a minimum of 2.7 years for the total trip time.

Prior work on faster round trips focused on electric propulsion transfer and the general rules for round trip interplanetary travel [Wertz, 2003]. The most important of these rules is what I call the Fundamental Constraint of Round Trip Travel:

> **The difference in the change in mission anomaly between the traveler and the home planet must always be an integral number of orbits, W.**

By changing from W = 1 to W = 0, a round trip to Mars can drop from 2.7 years to 5 months, but at a total delta V‡ cost of nearly 60 km/sec, about 5 times the delta V for a W = 1 Hohmann transfer mission. The purpose of the current work is to look for round trips to Mars and back that are intermediate in terms of both delta V and total round trip time.

Representative results of this assessment are shown in Table 1. Intermediate round trips (Scenarios F, G, and H) can provide a stay on Mars of 3 to 7 months with a total round trip time of 1.2 to 1.4 years and a total delta V of 3 to 4 times that of the traditional Hohmann round trip (Scenario A). If direct entry is used, the total delta V can be reduced by about a factor of 3.

Example	A	B	C	D	E	F	G	H
	Hohmann (W=1)	High Energy, W=1	High Energy, Direct W=0	Direct W=0 with Longer Stay	Outbound /Return both Indirect	Direct Outbound / Indirect Return	Direct Outbound / Indirect Return	Direct Outbound/ Indirect Return
Total Trip (months)	32.0	30.7	5.0	5.0	19.9	14.4	15.4	16.9
Mars Stay (months)	14.9	25.6	0.1	0.4	2.0	3.0	4.7	7.3
Tot. Delta V‡ (km/sec)	11.2	57.2	59.1	65.2	35.3	43.4	49.3	59.1
Delta V‡ 1 & 3 (km/sec)	5.6	28.6	29.5	32.6	17.7	14.5	16.8	20.7

Table 1. Key Parameters for Representative Round Trips to Mars. For additional parameters, see Table 2. See footnote for a discussion of delta Vs.

† We define *mission anomaly* as the angular position of the Home planet, Target planet, or the traveler with respect to some reference that can be regarded as fixed in inertial space. The reasons for introducing this is that we wish to talk about differences in angular positions among various objects and the changes in these angular positions over time. Therefore, we want to measure this angular position with respect to some fixed reference. This is somewhat different than the usual definition of *true anomaly* that is measured with respect to a potentially changing perihelion location.

‡ Throughout the paper, "round trip delta V" is the sum of 4 velocities: V1 = the initial delta velocity to leave the vicinity of the Earth on the outbound trip, V2 = the arrival delta velocity to match the orbital velocity of the target, V3 = the delta velocity to leave the vicinity of the Target on the return trip, and V4 = the arrival delta velocity to match the orbital velocity of the Earth. It assumes 4 impulsive thruster firings and does not include the delta V to leave or land on the Earth or the target. Circular, coplanar orbits for the Earth and the target planet are assumed throughout.

AN ANALOGY FOR INTERPLANETARY ROUND TRIP TRAVEL

My name is Marty. (Not really; but, as we'll see shortly, it's convenient.) Being both old and a tad "portly," I jog like a lethargic snail with a bandage on one foot. Let's assume I can jog (crawl) around the outer edge of the circular local high school track in 5.0 minutes. My friend, Earthy, runs backwards to keep from going too much faster than I, but still jogs around the inner edge of the track in 3.0 minutes. Thus, the basic parameters of our exercise program are:

Marty's speed	= 5 min/lap = 72 deg/min
Earthy's speed	= 3 min/lap = 120 deg/min
Relative speed	= 120 – 72 = 48 deg/min

If we start together, we will next be together after (360 deg)/(48 deg/min) = 7.5 min. This is called the *synodic period*. In one synodic period, Marty (the slower runner) will have gone 1.5 laps and Earthy will have gone 2.5 laps, i.e., exactly one lap more. In racing terms, Earthy "laps" Marty every 7.5 minutes.

Suppose on a particular day, Marty has forgotten his water bottle and wishes to borrow Earthy's. Earthy hands the bottle to Marty at the first opportunity, 7.5 min into the exercise. Marty hands it back to Earthy at the next opportunity, 7.5 min later (15 min total elapsed time), when they again return to being next to each other. Thus, the nominal trip time for the bottle to go from Earthy to Marty and back to Earthy is 7.5 min. Since the start of the exercise, Marty will have gone 3 laps and Earthy 5 laps. When it returns to its original owner, the water bottle (which, of course, will become the spacecraft in this analogy), will have gone 2.5 laps with Earthy + 1.5 laps with Marty = 4 laps, exactly 1 less lap than its owner. Therefore, in our terminology, W = 1.

Earthy is happy to help, but is a bit annoyed at not having his water bottle for an extended period. How can Marty return it more quickly? Here are 3 possible solutions:

Solution 1. Marty gets the bottle, takes a drink, and then sets the bottle on the ground. Earthy picks it up when he comes around next, 3 minutes after he handed it to Marty. Earthy will have made 3.5 laps and the water bottle will have made 2.5 laps, again the magic difference of 1 lap. (Notice that we don't really care where Marty is when Earthy gets the bottle back. He's elsewhere on the track and not a part of the problem at this point.) The two key points are that W = 1 once again and we've been able to speed up the round trip by slowing the water bottle. This increases the relative speed between Earthy and the water bottle to 120 deg/min, i.e., Earthy's rate around the track.

Solution 2. Just as he is about to pass Marty for the first time, Earthy tosses the bottle forward to him. Marty take a quick drink and hands it right back to Earthy. Now the elapsed time in which Earthy hasn't had the bottle is very short. Both Earthy and the bottle have made 2.5 laps of the track since the start of the exercise, such that the difference is now W = 0. The real key is that the bottle hasn't had to hang around for a long time (either with Marty or sitting on the side of the track) waiting for Earthy to make another full lap to catch up with it.

Solution 3. As soon as Marty gets the water bottle at 7.5 min, he begins cutting across the infield, such that he catches Earthy exactly opposite where they first met. This is somewhat intermediate in terms of time. Earthy gets the bottle back in only 1.5 min and Marty has plenty of time to get a drink. At the time he gets the water bottle back, Earthy has gone 2.5 + 0.5 = 3.0 laps and the bottle will also have gone 3.0 laps (or, at least, 3.0 trips around the center). Again, W = 0.

Our analogy to interplanetary round trips certainly isn't perfect. In interplanetary travel, the trip itself (i.e., the handoff) takes quite a bit of time. The outer planets both move slower and travel farther than the inner planets. Also, it takes just as much energy to slow a spacecraft as it does to speed it up. Thus, I can't "set the spacecraft down on the track" and wait for the Earth to swing by. I can, however, go out further from the Sun than the orbit of my target planet and travel more slowly than the target.

Nonetheless, the analogy does illustrate a few key points:

- No matter what, the difference in the number of laps taken by the water bottle and it's original owner (Earthy) must be an integer, W.

- Slowing down the spacecraft angular velocity can speed up the transfer (but not by a great amount).
- The real change in round trip time comes when we reduce W, the number of added trips the spacecraft takes, from 1 to 0.

It is the change in "lap differential" that lets us do quickly the transfer to Marty and back. What remains is to see whether "hand off and return" and "cutting across the infield" work for interplanetary travel.

THE FUNDAMENTAL RULE OF ROUND TRIP TRAVEL**

In round trip interplanetary travel, the traveler and the home planet begin and end together and, therefore, must have the same mission anomaly before and after the trip. This, in turn, implies the following Fundamental Constraint of Interplanetary Round Trip Travel:

The difference in the change in mission anomaly between the traveler and the home planet must always be an integral number of orbits, W.

- W = 0 or a positive integer for trips outward from the Earth
- W = 0 or a negative integer for trips inward from the Earth
- Using Hohmann minimum energy transfer orbits, W = 1 for round trips to Mars, 5 for round trips to Jupiter, and –1 for round trips to Venus. (See Wertz [2003].)

The round trip time is dominated by the value of W, with very little change caused by the applied delta V, until the value of W changes. At that point, there will be a change in round trip time of about a year for distant trips and much longer for nearby trips. This is illustrated for round trips to Jupiter in Fig. 1, which shows the change in both round trip and stay time as the total round trip delta V increases. Notice that the steps in round trip time are just a bit more than a year and that the first step (W = 5 to W = 4) requires only a small increase in delta V.

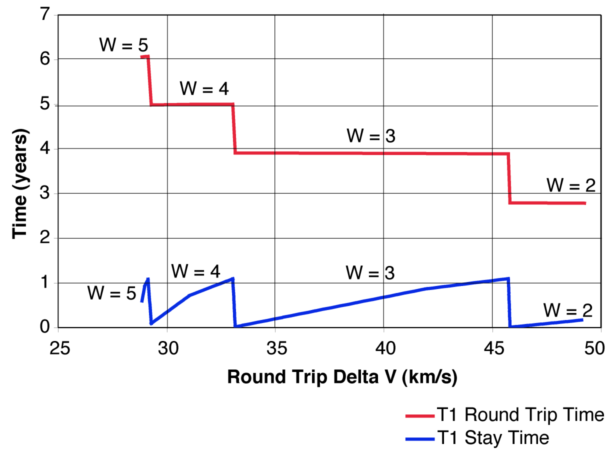


Fig. 1. Rapid Round Trips to Jupiter. The steps occur whenever the number of times the Earth must "lap" the traveler is reduced by 1.

The same effect is shown for Mars round trips in Fig. 2. As the total delta V increases, the amount of time spent on the surface of Mars also increases, but the total round trip time decreases only slightly. Once the threshold of W = 0 is reached, the total round trip time drops dramatically. Similar, but even more dramatic results are shown in Fig. 3 for a round trip to a hypothetical near-Earth asteroid at 1.1 AU. In this case, the delta V cost is modest while the reduction in round trip time is very large. For any objects which are near the Earth, the only realistic approach to round trip travel will be when W = 0.

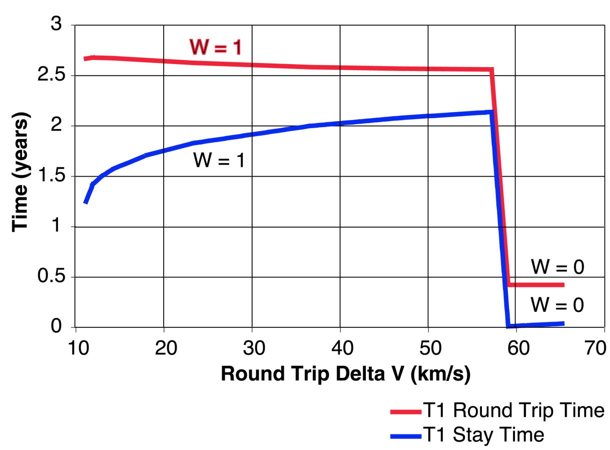


Fig. 2. Rapid, Direct Transfer Round Trips to Mars. In this case, going from W = 1 to W = 0 has a major impact on the total round trip time, but at a high cost in delta V.

** For a more extended discussion of this rule, other constraints on round trip travel, and it's implications for Hohmann transfer missions, see Wertz [2003].

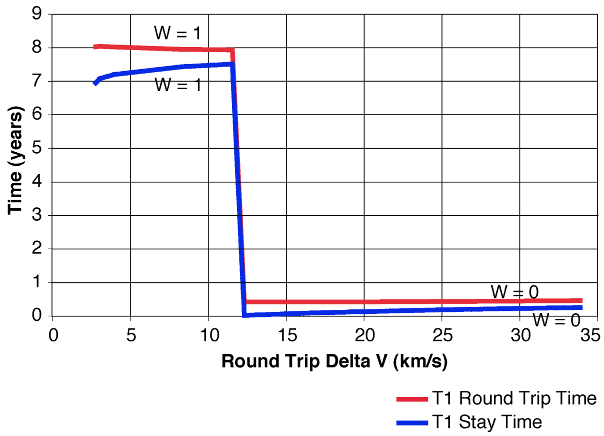


Fig. 3. Rapid, Direct Transfer Round Trips to a Near-Earth Asteroid. Here W = 0 represents the only realistic approach to round trip travel.

ROUND TRIP SIMULATIONS

In order to illustrate more clearly what is happening, we have put a series of simulations on the web at

http://www.smad.com/ Interplanetary_Round_Trip/simulations

The first four simulations on the website illustrate why the Mars curves in Fig. 2 have the behavior shown. The first simulation is "**Synodic Period**" which sets up the problem by illustrating successive opportunities for trips to or from Mars. Mars and the Earth first line up at opposition at the 3 o'clock position on the simulation. The Earth "laps" Mars 2.13 years later when they again line up at the next opposition at the 1 o'clock position.

The second simulation, "**Hohmann Round Trip**," illustrates the traditional process of using Hohmann transfer orbits both to and from Mars. Notice the lap counters in the lower right that keep track of the number of trips around the Sun since the start of the simulation for the Earth, Mars, and the traveler. The traveler starts out 95 days before opposition and arrives at Mars 160 days after opposition. The traveler now has no choice but to spend 450 days (1.23 years) in the vicinity of Mars (on the surface or in orbit), waiting for the next opportunity to return to Earth at approximately the time of the next opposition. Basically, the traveler must wait for the Earth to lap Mars so the return trip can be made. It's this added trip around the Sun that the Earth must make that makes W = 1. The return trip reverses the outbound process by beginning 160 days before the second opposition and arriving back at Earth 95 days after the second opposition, which is 970 days after leaving Earth.

The third simulation, "**High Energy/W=1,**" illustrates a particularly bad choice of travel plans. Here the delta V is increased greatly, but not quite enough. The traveler now leaves a bit later, at 75 days before opposition and arrives only a day after opposition. He now waits 775 days at Mars, nearly a full synodic period, before leaving 1 day prior to next opposition. The traveler arrives back at Earth 75 days after the second opposition. By adding a very large delta V, the one way transit time has been reduced from 255 days to just over 75 days, the time at Mars has increased from 450 days to 780 days, but the total round trip time has only been reduced from 970 days to 930 days. The traveler has still been "trapped" by the need for the Earth to make an extra trip around the Sun before he can return home.

The transition to W = 0 is shown in the fourth simulation, "**High Energy Direct/W=0**." By adding just a small amount more delta V relative to simulation 3, the traveler still leaves at about 75 days before opposition, but now arrives 6 days <u>before</u> opposition. Now things have changed dramatically. The traveler can now spend 12 days on Mars, leave 6 days after <u>the same opposition at which he arrived</u>, and return home 69 days later for a total trip time of only 150 days. This is how the transition to W = 0 occurs and why it so dramatically shortens the round trip time.

We do not have to make the round trip process symmetric, as is done in the first simulations. We could have traveled outbound as in simulation 3, arriving 1 day after opposition, and then returned via the trip in simulation 4, leaving at 6 days after opposition and, as in simulation 4, having a short, W = 0, trip. So long as the traveler leaves Mars in the general time frame of the opposition at which he arrived, then W = 0 and the total round trip time will be much shorter than for W = 1. As discussed below, there are many combinations of outbound and return trips which can make this happen, but all will require a much higher delta V than the traditional, W = 1, Hohmann round trip process.

THE TAXONOMY OF INTERPLANETARY ROUND TRIP TRAVEL

It is clear from the above that the value of W largely determines the time and conditions of interplanetary round trip travel, relative to each planetary opposition. (For a discussion of opposition timing and the synodic period relative to interplanetary travel see, for example, Wertz [2001].) This gives us a convenient way to apply a "taxonomy" or classification scheme to interplanetary round trips.

Typically, the lowest delta V for interplanetary travel will be via a Hohmann transfer trajectory[††]. The Hohmann transfer orbit is tangent to the Earth's orbit on one side and to the orbit of the target planet on the other side. Depending on the destination, this *Hohmann round trip* will have a specific value of W, i.e., 5 for Jupiter, 1 for Mars, and –1 for Venus. (To simplify the discussion, we will concentrate on outbound trips. See Wertz [2003] for a discussion of inbound trips.)

If W is an odd number, then the stay time on the planet will be centered around conjunction when the target planet is on the opposite side of the Sun from the Earth. This tends to make communications difficult, though not impossible, because of both the distance and interference from the Sun. If W is an even number or 0, then the stay on the planet will be centered at or near opposition when the Earth and the target are lined up on the same side of the Sun. This is best for communications and any possible visual monitoring of, for example, weather on Mars.

As the above examples have shown, adding additional energy does very little to change the total round trip time, until the value of W changes. Then we get a step function in total trip time. Therefore, we define a *rapid round trip* (RRT) as one with a value of W lower in absolute magnitude than for a Hohmann round trip to the same destination. Similarly, a *quickest round trip* (QRT) is one for which W = 0. This is the fundamental requirement for the fastest round trips and the only realistic way to get to objects that are nearby and return home. Finally, an *interplanetary train schedule* (ITS) is a table or plot showing departure and arrival times relative to opposition and the cost, in terms of delta V, for various interplanetary round trips.

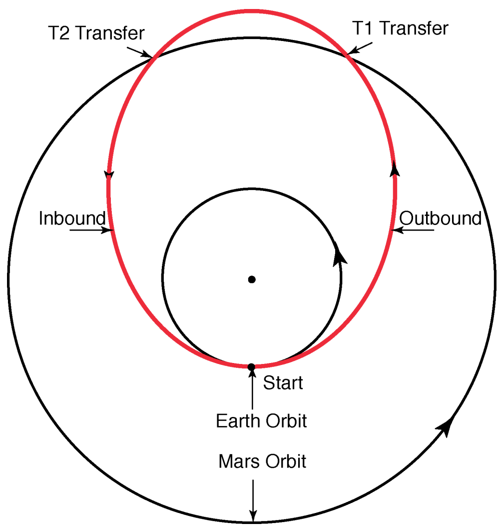
Generally, though not necessarily, as we apply more delta V we can leave later and arrive earlier relative to a given opposition. We can get a good sense of what is achievable by looking at our ITS. For a given Mars opposition, if we can arrive early enough to spend as long as necessary on Mars and still catch a trip back near that opposition, then W = 0, and the trip will be relatively short in total duration. If we arrive too late or don't have enough delta V available (the equivalent of interplanetary currency), then we will have to wait about 1 synodic period until the next opposition in order to return. This will give us lots of time, possibly more than we would like, to hang out on Mars or at the train station.

The Hohmann round trip is well-defined because it is tangent at both ends and traveler must be at the Earth and the Target when the respective planets are there. It is also efficient, because we are applying delta V in the direction of motion and not using it to change direction which effects the eccentricity but doesn't change the semi-major axis or total energy of the orbit. As we apply more delta V, we loose efficiency but can reduce the time (particularly if we get to a W boundary) and increase the number of options available to the traveler.

As shown in Fig. 4, there are two options, called T1 and T2, for transfer orbits tangent to the inner planet and two options, T3 and T4, for transfer orbits tangent to the outer planet. We could, of course, travel out or back on any of the paths, so there are really 8 choices (4 outbound and 4 inbound) of different orbit transfers with the transfer leg tangent at one end or the other. (We could also have transfers that are not tangent at either end, but thus far we have not found any time or energy advantage to doing this.) Once we have picked a specific transfer type, we can then create an ITS for that type of transfer which gives us the

[††] Depending on the conditions of a particular trip, there may be other approaches with lower delta V, such as a bi-elliptic transfer, planetary fly-by, or Martin Lo's "Interplanetary Superhighway" [Wertz, 2001; Vallado, 2001; Lo, 2001, 2002]. Typically, though not necessarily, these will involve longer times, additional travel constraints, or both.

departure and arrival times relative to opposition as a function of the delta V cost. The equations for this and the results obtained are given below.



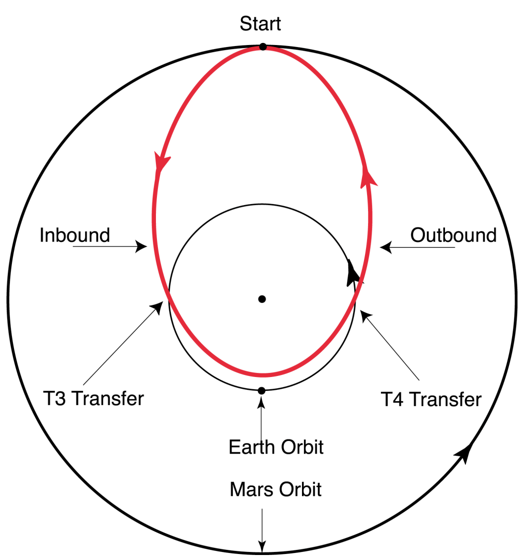


Fig. 4. Alternative Transfer Options (not drawn to scale). T1 and T2 transfers are tangent at the inner planet, but not the outer. T3 and T4 are tangent at the outer planet, but not the inner. See text for discussion and timing formulas relative to opposition.

For round trip travel, the inbound and outbound legs are unrelated, except for the obvious constraint that the traveler must leave the target planet at some time after he has arrived. The inbound and outbound legs are not part of the same transfer orbit, so we have two distinct decisions — how to get to the target and how to return. To make the discussion easier, we will assume the transfer begins tangent to the planet it's departing and not tangent when it arrives. (We can make any of the transfers simply symmetric reflections of these and have done so in some of the examples.)

We call a transfer leg *direct* if the traveler never crosses the orbit of the destination planet, i.e., a T1 transfer outbound or T3 transfer inbound. If the traveler crosses the orbit of either planet and then arrives at the planet at the second crossing (T2 outbound or T4 inbound), then it is an *indirect* transfer. Although it seems strange at first, both T2 and T4 indirect transfer methods can, at times, reduce the round trip time by increasing the relative angular velocity between the traveler and the home planet. For example, in a W = 1 mission to Mars, the traveler has to hang around on Mars while waiting for the Earth to lap Mars. Using a T2 transfer slows the traveler, which increases the relative angular velocity between the traveler and the Earth, and allows the Earth to catch up more quickly. In the track analogy, this is equivalent to setting the water bottle down and letting Earthy catch up with it more quickly. We can't really "set it down on the track" in astrodynamics, but going beyond the orbit of Mars will reduce the average angular velocity. Slowing the traveler speeds up the round trip time in W = 1 missions.

In a W = 0 mission, a T4 indirect transfer can be useful by speeding up the traveler. This is equivalent to "cutting across the infield" in our track analogy and lets the traveler catch up with the Earth. T1 and T3 transfers are also useful for the W = 0 mission because both can provide transfer between planets at a higher angular rate than the Hohmann transfer provides.

W = 0 DIRECT AND INDIRECT MISSIONS

As illustrated in Fig. 5, the following must be true for W = 0 missions:

> **Over the mission duration for W = 0, the average angular speed of the Home planet and the traveler must be the same.**

Any period of slower angular speed on the part of the traveler, including stay time at the Target, must be compensated by periods of faster angular speed in order to get back home. Similarly, periods of higher angular speed on the part of the traveler must be compensated by lower angular speed to allow the Home planet to catch up. W = 0 transfers enable short, flexible round trips. Mission durations and stay times will be limited primarily by the amount of delta V that we are willing to use. (In W = 1 missions, the mission duration and stay time are driven primarily by the need for the Earth to make one more revolution than the traveler.) W = 0 missions are practical over the approximate region from Venus on the sunward side to Mars on the outward side.

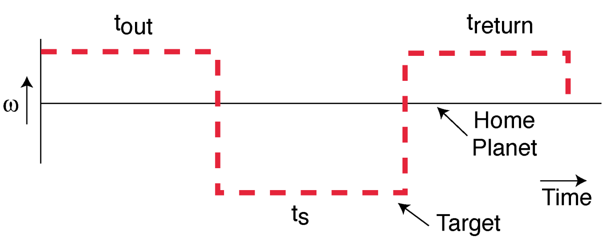


Fig. 5. For W = 0 missions, the difference between the angular velocity, ω, of the traveler and the Home planet must integrate to 0. This is true irrespective of the shape of the angular velocity curve for the Home planet, i.e., irrespective of the eccentricity of the Home planet's orbit.

The W = 0 transfer is achievable, but requires a different regime (and more energy) than Hohmann round trips. This issue can be seen by examining Fig. 6, which shows the angular rates for a Hohmann transfer from the Earth to Mars. The traveler starts out by speeding up and going at a faster angular rate than the Earth. As he goes outbound to Mars his rate gradually slows and he again must speed up to catch up with Mars rate when he arrives at his destination. If the difference between the transfer orbit rate and the Home planet rate in Fig. 6 is to average to 0, then we can only use the left third or so of the plot. By visual inspection it appears that a Hohmann transfer out to the orbit of Mars would support a W = 0 mission to about 1.2 AU from the Sun. That is, if we stopped at about 1.2 AU, turned around and came back on the "other side" of the same orbit, the average angular rate would be about the same for the traveler and the Home planet. This is another way of measuring the cost of orbit transfer. A W = 0 transfer to 1.2 AU from the Sun will cost about the same delta V as a Hohmann minimum energy transfer to Mars at about 1.5 AU.

The logic of Fig. 6 applies only to direct transfer missions. As can be seen in Fig. 2 above, direct transfer missions to Mars dramatically reduce the round trip time, but have a very high delta V cost and allow only a short time on Mars, probably no more than a few weeks. This may be appropriate for some missions. However, we would like to find ways to use less delta V and allow a greater stay time on Mars while still maintaining some of the advantages of the direct W = 0 mission. The solution is the indirect transfer mission in which one or both of the transfer legs involve going

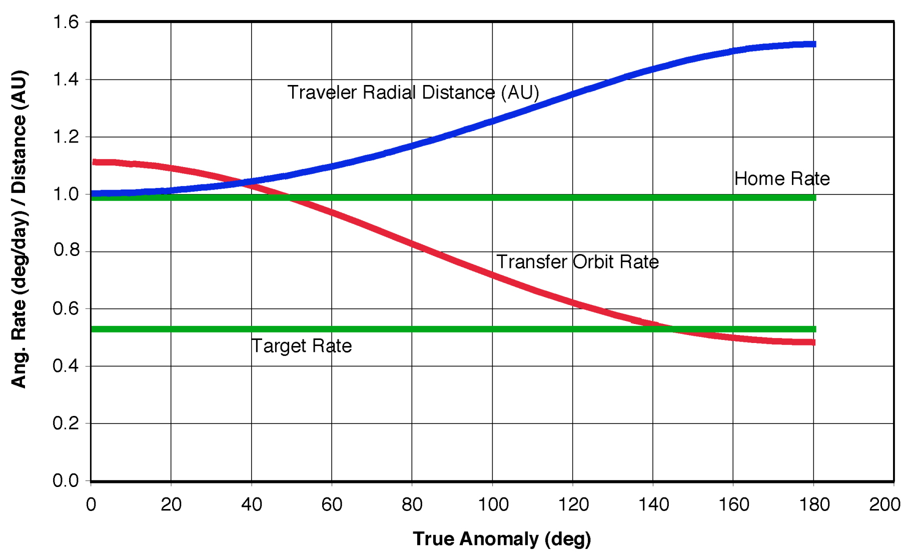


Fig. 6. Angular rates for a Hohmann Transfer Mission to Mars. If the constraint of Fig. 5 is to be satisfied, then we must use only the left hand portion of this figure.

inside the orbit of the Earth such that the traveler's angular velocity is considerably faster than the Earth and, therefore, can make up for additional time spent on Mars when the traveler and Mars are going at a substantially slower angular velocity.

This mission type is illustrated in the fifth simulation, called "**Direct Outbound/Indirect Return**," on the website identified above. This is an example of asymmetric mission design. On the outbound leg, we use the same direct transfer as was used in the 3rd simulation, leaving 75 days before opposition and arriving just after opposition. However, the traveler now spends 90 days or more on the surface of Mars and returns via a T4 indirect transfer back to Earth. The return trip now takes 250 days, crosses the Earth's orbit and catches up with the Earth after having passed perihelion near or inside the orbit of Venus. This is a W = 0 "compromise mission" that is intermediate in terms of required delta V, time on Mars, and total round trip time relative to the very slow Hohmann round trips and the very fast, high delta V, direct W = 0 missions. Figure 7 shows the options available for W = 0 indirect transfer missions in the same format as Figs. 1, 2, and 3. With a total delta V of 35 km/sec or more, we can achieve stay times of several months and a total round trip time of 1.0 to 1.5 years.

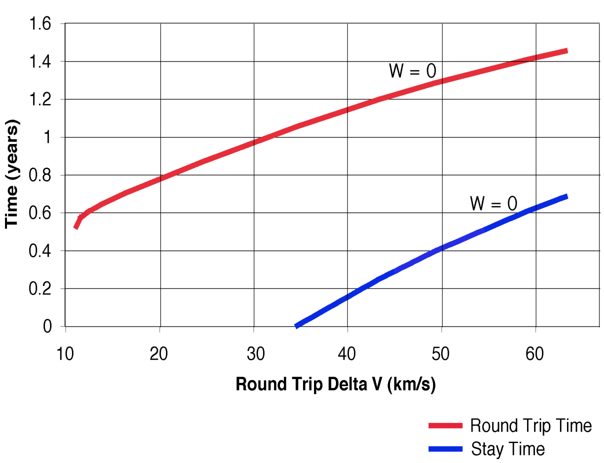


Fig. 7. W = 0 Indirect Transfer Mission to Mars. In this case, the return trip swings inside the Earth's orbit to allow the traveler to catch up with the Earth.

CREATING THE INTERPLANETARY TRAIN SCHEDULE

For a given transfer orbit, the departure time and arrival time relative to opposition are determined by the need to match the positions of the traveler, the Home planet, and the Target. As the delta V increases, each of the transfer types, T1 to T4, leads to a well-defined sequence of departure and arrival times that must be met or the traveler must wait for the next opposition. I call this the "Interplanetary Train Schedule" (ITS) because it gives departure times, arrival times, and the cost. Of course, unlike our Earth-bound trains, these trips must run on time, although some variation can be accommodated by adjusting the transfer velocity.

For establishing the general characteristics of the ITS, we assume that the Home planet and the Target are moving at a fixed angular velocity, ω_H and ω_T, respectively. Because the planetary orbits are not truly circular, the actual departure and arrival dates can vary by several weeks. However, the general characteristics remain the same.

For the outbound segment, the traveler must start at the Home planet and arrive at the Target. Therefore, the start time, T_{start}, and start mission anomaly, θ_{start}, and arrival time, T_{arrive}, and arrival mission anomaly, θ_{arrive}, relative to opposition are related by

$$\theta_{start} = T_{start}\,\omega_H \tag{1}$$

$$\theta_{arrive} = T_{arrive}\,\omega_T \tag{2}$$

For the traveler to start at the Home planet and arrive at the Target, we must have

$$\Delta\theta = \theta_{arrive} - \theta_{start} = \omega_{transfer}\; t_{transfer} \tag{3}$$

where $\omega_{transfer}$ is average angular velocity over the transfer segment and $t_{transfer}$ is the transfer time. Given a specific set of transfer parameters, the start and arrival times relative to opposition, T_{start} and T_{arrive}, are:

$$T_{start} = t_{transfer}\;(\omega_T - \omega_{transfer}) / (\omega_H - \omega_T) \tag{4}$$

$$T_{arrive} = T_{start} + t_{transfer} \tag{5}$$

The start and arrival mission anomalies are then given by Equations (1) and (2).

Given a specific transfer scenario, Eqs. (1) through (5) determine the departure and arrival times of the outbound and return segments relative to opposition. Of course, small corrections will be needed to account for the non-zero eccentricity of real orbits. For example, relative to a perfectly circular orbit, the Earth can be as much as 2 days ahead or behind and Mars can be as much as 20 days ahead or behind.

While the above formulas are well known, they have been applied largely in the vicinity of minimum energy transfers. For higher energy, shorter duration missions we use the above formulas to construct the ITS of transfer times to the planets as a function of the applied delta V.

Table 2 shows representative examples of the ITS for the various options described in the previous sections. In this case, the formulas above have been applied to the Mars opposition of Jan. 29, 2010, in order to provide specific dates for the various steps, recognizing that again we have not taken into account the adjustments due to eccentricity or any mid-flight corrections.

An alternative approach to showing the train schedule is illustrated in Fig. 8. In this and subsequent figures, the vertical axis is the delta V (V1 + V2 on the outbound leg and V3 + V4 on the return). The horizontal axis is the time relative to opposition, represented by the vertical blue line at 0. The next opposition is one synodic period later shown by the vertical blue line on the right. The green line on the x-axis on the left represents the range of departure times from Earth. The arrival times at Mars are along the red line starting just to the left of opposition. The green line that is the mirror image of the red arrival curve shows the departure times from Mars. The red line on the x-axis is the arrival at Earth corresponding to these departure times. The black lines shown specific

EXAMPLE

		A	B	C	D	E	F	G	H
		Hohmann (W=1)	**High Energy, W=1**	**High Energy, Direct W=0**	**Direct W=0 with Longer Stay**	**Outbound and Return both Indirect**	**Direct Outbound/ Indirect Return**	**Direct Outbound/ Indirect Return**	**Direct Outbound/ Indirect Return**
Outbound									
Depart	(date)	24-Oct-09	13-Nov-09	13-Nov-09	13-Nov-09	1-Apr-09	11-Nov-09	12-Nov-09	13-Nov-09
Transfer	(days)	259	78	75	70	272	95	87	76
Arrive	(date)	10-Jul-10	30-Jan-10	27-Jan-10	22-Jan-10	28-Dec-09	14-Feb-10	7-Feb-10	28-Jan-10
Delta V1	(km/sec)	2.94	10.60	11.00	12.33	12.22	7.66	8.83	10.90
Delta V2	(km/sec)	2.65	18.01	18.55	20.30	5.43	13.73	15.51	18.41
Mars Stay									
Duration	(days)	454	778	2	13	62	90	144	221
Duration	(months)	14.9	25.6	0.1	0.4	2.0	3.0	4.7	7.3
Return									
Depart	(date)	8-Oct-11	18-Mar-12	30-Jan-10	4-Feb-10	1-Mar-10	15-May-10	1-Jul-10	6-Sep-10
Transfer	(days)	259	78	75	70	272	251	238	217
Arrive	(date)	23-Jun-12	4-Jun-12	15-Apr-10	15-Apr-10	27-Nov-10	22-Jan-11	23-Feb-11	11-Apr-11
Delta V3	(km/sec)	2.65	18.01	18.55	20.30	5.43	6.89	7.95	9.80
Delta V4	(km/sec)	2.94	10.60	11.00	12.33	12.22	15.14	17.03	20.04
Perhelion	(AU)	1.00	1.00	1.00	1.00	0.65	0.52	0.44	0.33
Total Mission									
Total Trip	(days)	972	934	153	152	606	437	468	514
Total Trip	(yrs)	2.66	2.56	0.42	0.42	1.66	1.20	1.28	1.41
Tot DV1-4	(km/sec)	11.19	57.21	59.10	65.24	35.30	43.41	49.32	59.15
Tot DV1 & 3	(km/sec)	5.59	28.61	29.55	32.62	17.65	14.54	16.78	20.70

Table 2. Representative "Train Schedules" to Mars. This is a sample schedule built around the Mars opposition of Jan. 29, 2010.

sample trips, with the mark in the center of the line showing the split between V1/V2 on the outbound trip and between V3/V4 on the return trip.

The traveler can take any outbound trip and can then return to Earth on any return trip that leaves after he has arrived. The examples that we have used in the sections above are illustrated here. Scenario A, the lowest black line marked with squares, is the Hohmann transfer orbit with the lowest total delta V. The arrival at Mars is 160 days after opposition, which is well to the right of any of the green departure lines. Therefore, the traveler must wait until 160 days before the next opposition (i.e., W = 1) to depart for Earth. The black line marked by the triangles is Scenario B, which is a particularly bad choice in terms of round trip times. The traveler arrives at Mars much earlier than in A, but not quite early enough to catch a ride back at the same opposition. Here again, the traveler waits for an extended period on or near Mars and returns at the next opposition with W = 1. The total delta V has been greatly increased, but the total round trip time is only marginally reduced. Finally, Scenario D is the line with the circle markers. The traveler arrives just before opposition, stays a very brief period, and returns to Earth at the same opposition with W = 0.

The advantage of this type of plot is that we can get a sense of the available options. While tabular examples provide specific scenarios, it is clear from the plot that we can arrive at Mars at any point on the red line and leave at any point on the green line that is to the right of where we arrived. In the vicinity of Scenario D, the curve is extremely steep. This implies that significantly longer W = 0 stays on Mars will come at a very high cost in terms of added delta V.

Figure 9 shows the same information as Fig. 8, with the addition of information about the split of delta V between the first and second burns on each leg of the trip. The yellow line on the left shows the V1/V2 split and the yellow line on the right shows the V3/V4 split. For example, if we draw a single trip line, such as the Scenario B line shown by the triangles, the yellow line shows that V1 is about 8 km/sec and V2 about 16 km/sec. This is important because the second delta V on each leg, which occurs at arrival, can potentially be done entirely or partially by direct entry or aerobraking, rather than by use of rockets and propellant. Thus, there is a potential advantage to a trip that splits the total delta V into a smaller amount on the departure burn and a larger delta V on arrival.

Figure 10 is an expanded view of a single Mars opposition showing both direct and indirect transfers with W = 0. For W = 0, there is no advantage to going outside the orbit of Mars and slowing the traveler as occurs with a T2 transfer. Thus, the only trips shown are direct transfer or an indirect transfer where the traveler goes inside the orbit of the Earth in order to travel at a higher angular rate. For a given delta V there are 2 significantly different departure times from Earth (and corresponding arrival times at Mars) depending on whether the transfer is direct or indirect. The different arrival times are shown by the two red lines that begin together at the Hohmann transfer delta V and proceed upward to the left. The Hohmann transfer orbit is tangent to the planetary orbits at both the Earth and Mars, so there is no distinction between direct and indirect Hohmann transfers. As the delta V gets larger for the direct transfer mission, the departure times change relatively little, but the traveler arrives significantly earlier. However, as we have seen in Figs. 8 and 9, this curve becomes very steep as the arrival time approaches opposition.

In contrast, departure times for the indirect transfer move more quickly to the left as the delta V increases. As the delta V becomes larger, the travel times remain somewhat long because of the time spent inside the Earth's orbit, but the arrival time at Mars becomes substantially earlier relative to opposition.

The mirror image of these two curves are the green lines that show the departure times from Mars for both direct and indirect transfers. Again, the traveler can arrive on any of the red lines and then leave on any green line that is later than the arrival time. A particularly interesting example is the asymmetric trip shown as Scenarios F, G, and H in the tables and represented in Fig. 10 by the trip line with the triangle markers. Here the traveler uses a direct transfer outbound with V1 much smaller than V2. He then uses an indirect T4 transfer to return home and again has V3 significantly smaller than V4. Thus, particularly if

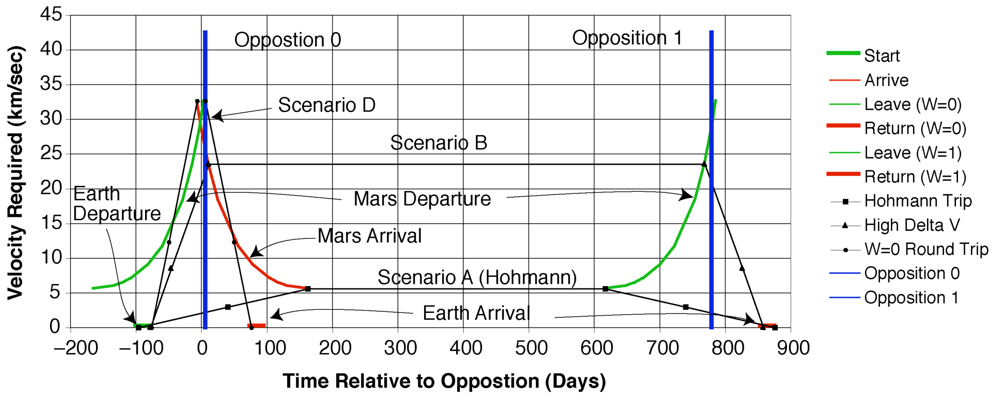


Fig. 8. Graphical Train Schedule to Mars with Transition from W = 1 to W = 0. For both outbound and return flights, the traveler leaves on a green line and arrives on a red line.

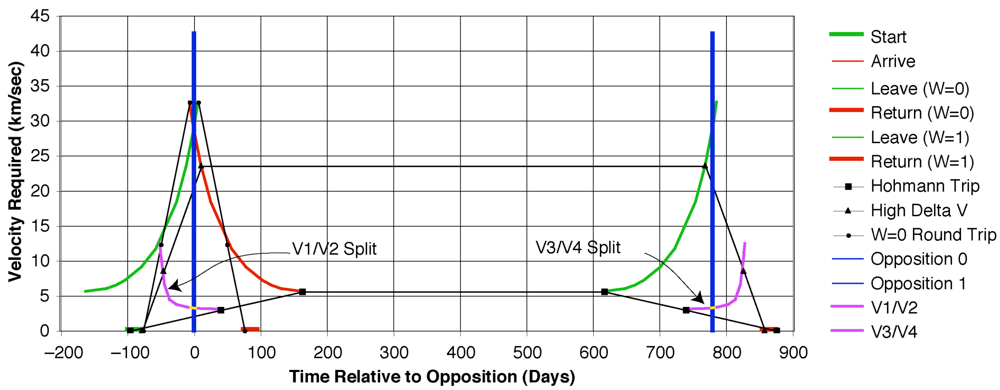


Fig. 9. Train Schedule to Mars with Velocity Breakdown. The yellow line separates the first and second burns. On the left, V1 is below the yellow line and V2 above it. On the right, V3 is above the yellow line and V4 below it.

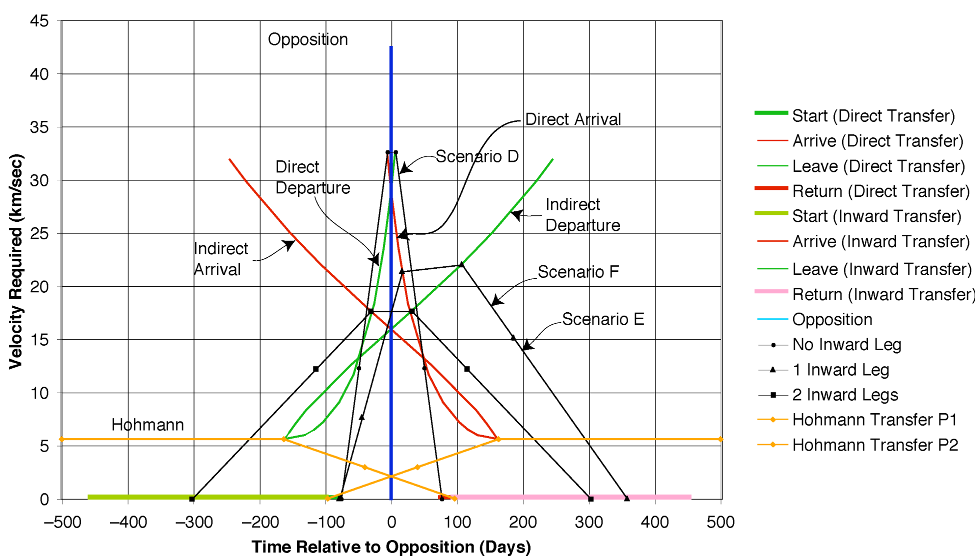


Fig. 10. W = 0 Train Schedule to Mars. For W = 0, the traveler arrives on any red line and leaves on a green line to the right, i.e., later in time. The markers on the representative trip lines in black are the V1/V2 split and the V3/V4 split.

V2 and V4 can be done partially or entirely by direct entry or aerodynamic braking, then these scenarios can provide rapid interplanetary round trips at moderate energy with a stay on Mars of reasonable duration.

EXAMPLE: NEAR-TERM, "LOW-COST" HUMAN MISSION TO MARS

A key problem with human Mars missions is the need for life support and radiation protection for a 2.7 year (970 day) mission duration. This is both expensive and inherently dangerous. Reducing the mission to 5 months by using direct transfer both ways is an interesting possibility, but would take very large delta Vs.

An alternative approach is a possible 2-phase human mission to Mars. The descent module, exploration equipment, extra life-support equipment and supplies, and equipment for the return to Earth would all be sent to Mars on a Hohmann low-energy transfer at Opposition #1. All of the equipment would be tested after it's arrival in Mars orbit or on the surface of Mars. The astronauts then travel at the second opposition, using one of two possible scenarios:

- Short Scenario: 70 day direct transfer, 13 to 20 day stay on Mars, and 70 day return (~150 day total mission duration)
- Moderate Scenario: 75 to 95 day direct transfer, 90 to 220 day stay on Mars, and 215 to 250 day indirect return (435 to 515 day total mission duration)

Most of the mass needed for the mission is transferred to Mars at minimum energy. The people are transferred on a minimum time trajectory. The total amount of human life support required is reduced from 970 days to between 150 and 500 days, i.e. a reduction by a factor of 2 to 6.

While this may or may not be the correct choice of mission profile for the first human missions beyond the vicinity of the Earth, it is an option that should be considered. It suggests a new paradigm for future, low-cost rapid human exploration of the Solar System that should be given sufficient consideration to understand the potential, the limitations, and the technology needs.

CONCLUSIONS

The design of interplanetary round trip missions is driven primarily by the fundamental constraint that the difference in the change in mission anomaly between the traveler and the Home planet must be an integral number of orbits, W. This constraint holds irrespective of the transfer method – i.e., direct transfer, electric propulsion spiral, multiple planetary fly-bys, or nuclear super rockets.

For W = 1, the total trip time is driven by the need to allow the Earth to make one more revolution around the Sun (relative to the traveler) during the trip. This constraint is needed to get the traveler back to the Earth. Slowing the angular velocity of the traveler by taking the spacecraft out beyond the orbit of the Mars can <u>reduce</u> the total trip time, but not by much.

For W = 0, there are much faster round trip missions with greater timeline flexibility at a cost of 2 to 10 times the delta V of minimum energy missions. This can bring the Mars round trip time down to 5 months or less, at a high delta V cost. Intermediate round trips (in terms of both duration and delta V) exist that provide 3 to 7 months on Mars with a total round trip time of 14 to 17 months.

All minimum energy outward round trips using Hohmann transfers are 2 years or longer in duration, which is rather long for most human travel applications. Therefore, realistic human flight on a regular basis may require delta Vs that are 2 to 10 times that of minimum energy (Hohmann transfer) missions.

Interplanetary round trip mission design is a relatively new field with interesting possibilities. While the general rules are now known, many detailed design elements are yet to be determined. For example, what is the relationship between the interplanetary round trips described here and the Interplanetary Superhighway missions described by Lo [2001, 2002]? The goal of this paper is not to advocate a specific mission profile, but rather to point out the range of options that exist and the need to explore these options further as a basis for intelligent design of future human interplanetary flight and the technology needed to enable or sustain it.

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