AIAA/AAS Astrodynamics Specialist Conference and Exhibit
5-8 August 2002, Monterey, California

AIAA 2002-4422

PRELIMINARY ANALYSIS AND DESIGN OF POWERED EARTH – MARS CYCLING TRAJECTORIES

K. Joseph Chen,* Damon F. Landau,* T. Troy McConaghy,† Masataka Okutsu,†
and James M. Longuski‡
School of Aeronautics and Astronautics, Purdue University
West Lafayette, Indiana 47907-1282
and
Buzz Aldrin§
Starcraft Enterprises
Los Angeles, California 90024

We discuss preliminary results on constructing a powered cycler from semi-cycler trajectories. We present a powered cycler with reasonable transfer times and low encounter velocities. In addition, we develop a metric for evaluating cycler designs in comparison to other mission-to-Mars scenarios. The metric suggests that as vehicle mass (with respect to propellant mass) increases, the most advantageous system progresses from a "Design Reference Mission" scenario to Semi-Cyclers to Cyclers, which is highly indicative of how a human Mars transportation system might evolve.

Nomenclature

a = semimajor axis, km
f = comfort factor, $(m_{transport} + m_{comfort}) / m_{transport}$
GM = gravitational parameter of planet with mass M, km^3/s^2
g = standard acceleration due to gravity at Earth's surface, 9.80665 m/s^2
I_{sp} = specific impulse, s
m = mass, mt (metric tons)
n = number of rocket stages
V_∞ = hyperbolic excess speed, km/s
ΔV = instantaneous change in velocity, km/s
μ = mass fraction

Subscripts

0 = initial
as = aeroshell
comfort = refers to mass that is used solely for safety or comfort of astronauts
cv = Cycler Vehicle
E = Earth
f = final
loose = loose parking orbit
M = Mars
p = propellant
pay = payload
peri = periapsis
stage = stage of a rocket
struc = structure
surf = surface of a planet
taxi = rocket used to transport mass from the surface of a planet to the Cycler Vehicle or vice versa.
transport = refers to mass that is transported from one planet to the other

Introduction

SINCE the late 1960s, numerous Earth-Mars circulating trajectories have been developed and proposed.[1-10] These concepts can be separated into two categories – the cyclers and the semi-cyclers. Both types of trajectories employ gravity assists to reshape and turn the orbits so that the spacecraft repeatedly encounters Earth and Mars. The main difference between the two types is that the semi-cyclers remain in an orbit about Mars for a period of time before returning to the Earth, while the cyclers perform only flybys at each planet.

---

[*] Graduate Student.
[†] Graduate Student, Student Member AIAA, Member AAS.
[‡] Professor, Associate Fellow AIAA, Member AAS.
[§] President, Fellow AIAA.

One notable cycler trajectory is the Aldrin Cycler, proposed in 1985.[4] The Aldrin Cycler can provide fast transfers to Mars (in which case it is called the Outbound Cycler) or fast transfers back to Earth (in which case it is called the Inbound Cycler).

Two cycler vehicles, one on each cycler trajectory, would allow a visit to each planet every Earth-Mars synodic period (about 2.14 years). The transfer time is typically less than 6 months. At each flyby, smaller vehicles dubbed "Taxis" rendezvous with the cycler vehicles to transport astronauts and goods to and from each planet.

The main drawback of the Aldrin Cycler is the moderate to high Mars flyby V_∞ (ranging from about 7 km/s to 12 km/s). These high V_∞ can make Taxi rendezvous with the cycler vehicle very costly. The semi-cyclers were developed partly to circumvent this disadvantage of the Aldrin Cycler.

Since the semi-cycler is placed in an orbit about Mars, the Taxi rendezvous is less costly. However, because of this orbit insertion, there will be a compromise on the transit times, which are typically longer for semi-cyclers than for cyclers. In addition, there is the extra propellant cost for capture and escape from the planet.

In October of 2001, Aldrin proposed connecting several semi-cycler trajectories into a continuous full cycler. The resulting trajectory combines the advantages of the cyclers and the semi-cyclers, while lessening the undesired features from both.

In this paper, we summarize some of our preliminary results and findings on linking the semi-cyclers. Our analysis is aided by several software tools developed at Purdue University and the Jet Propulsion Laboratory (JPL). In addition, we compare cycler trajectories to other known Earth-Mars mission architectures using our evaluation metric.

Methodology

To design cycler and semi-cycler trajectories, we first use the Satellite Tour Design Program (STOUR),[11] a conic trajectory propagator, to interactively construct trajectories. STOUR is a software tool that was originally developed by JPL for the Galileo mission tour design. This program was later enhanced and extended at Purdue University.

After STOUR design, we begin preliminary optimization with JPL's ballistic optimizer, the Mission Design and Analysis Software (MIDAS).[12] MIDAS is a patched-conic interplanetary trajectory optimization program that is able to minimize the total ΔV by varying event times (i.e. launch, flyby, and arrival dates). MIDAS is also capable of adding and deleting deep space maneuvers.

In addition to optimizing ballistic trajectories, we can also design and optimize low-thrust versions of cyclers with our Gravity-Assist Low-Thrust Local Optimization Program (GALLOP),[13-15] which maximizes the final spacecraft mass. We may use GALLOP to optimize trajectories from STOUR and MIDAS, as well as candidate guesses found by other means.

Another analytical tool we currently use is the Radial Distance Plot. This plot shows the distance of the spacecraft from the Sun with respect to time, along with the positions of the Earth and Mars, and Earth-Mars opposition dates. Besides being a "sketchpad" of new cycler ideas, such plots also help us validate the repeatability of promising candidate cycler trajectories.

Semi-Cyclers

Several semi-cyclers have been proposed, most notably the ones developed by Bishop et al.[7] and Aldrin et al.[10]

The Aldrin et al. proposal includes two versions of semi-cyclers. In the first version (Version I), the Cycler Vehicle leaves from an orbit about Mars, encounters the Earth twice, then returns to an orbit about Mars. The transit times between the two planets range from about 6 months up to about 9 months, and the entire sequence takes two synodic periods. The second version (Version II) is similar to the first one, except there are three Earth flybys separating the Mars departure and arrival. The time of flight between the first two Earth encounters is 1 year, while the time between the second and third Earth encounters is 6 months. Version II semi-cyclers have Mars flyby V_∞ that range from about 2 km/s to 7 km/s, and Earth encounter V_∞ that range from about 3 km/s to about 5 km/s. The entire sequence takes two synodic periods, thus at least two vehicles are needed to provide Earth-Mars and Mars-Earth transfers every synodic period

Out of these three candidate semi-cyclers, we choose to patch together Version II semi-cyclers into a full cycler. The other semi-cyclers may have merit in constructing full cyclers, but these considerations will have to be addressed in a future work.

Table 1: Trajectory summary of patched semi-cyclers (from STOUR)

Encounter	**Date (mm/dd/yyyy)**	**V_∞ or ΔV^b (km/s)**	**Altitude (km)**	**B-plane Angle (deg)**	**Orbit Period (days)**	**TOF (days)**
M-1	11/29/2013	3.960	200	-1.29	576	start
E-2	7/25/2014	4.891	15480	-74.31	365	238
E-3	7/26/2015	4.891	300000	90.00	365	365
Man[a]-1	**7/29/2015**	**0.340**	n/a	n/a	n/a	n/a
E-4	1/23/2016	5.223	36658	-128.94	471	178
M-5	9/26/2016	4.886	36598	140.97	458	247
M-6	7/1/2020	4.887	3428	-128.33	479	1374
E-7	1/22/2021	5.165	41536	72.15	365	205
E-8	1/22/2022	5.165	1000000	-150.00	371	365
Man[a]-2	**1/25/2022**	**3.973**	n/a	n/a	n/a	n/a
E-9	7/27/2022	8.651	5605	120.70	568	182
M-10	4/5/2023	5.470	**128[c]**	-176.06	458	252
M-11	1/8/2027	5.472	n/a	n/a	n/a	1374

[a] ΔV maneuver.
[b] ΔV are in bold.
[c] 200-km altitude constraint not met.

Table 2: Trajectory summary of optimized low-thrust cycler[a] (from GALLOP)

Encounter	**Date (mm/dd/yyyy)**	**V_∞ (km/s)**	**Altitude (km)**	**TOF (days)**
E-1	12/08/2015	4.876		
M-2	10/26/2016	4.461	52204	323
M-3	06/06/2020	4.303	200[b]	1320
E-4	01/06/2021	4.727	1994	214
E-5	01/21/2022	5.387	200[b]	380
E-6	07/24/2022	5.220	2648	184
M-7	06/11/2023	2.381	200[b]	322
M-8	09/17/2026	3.229	5818	1193
E-9	05/17/2027	4.228	8017	242
E-10	05/16/2028	4.227	22861303	365
E-11	11/18/2028	4.327		185
Total ΔV =	2.55 km/s			

[a] Initial mass is 75.0 mt, final mass is 69.4 mt, for Isp of 3000 seconds.
[b] At 200-km altitude constraint.

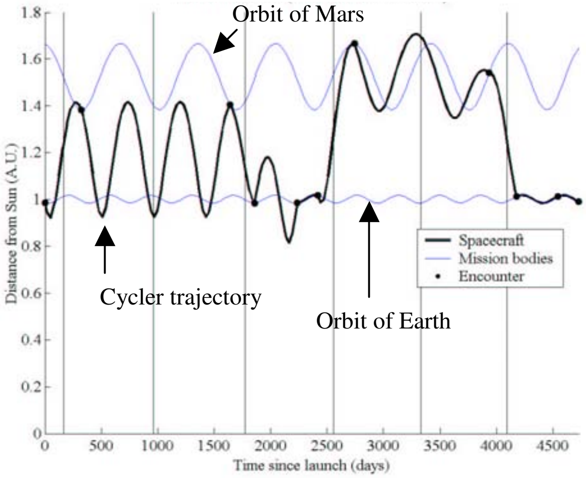

Fig. 1: Radial distance vs. time (for 2013 launch). The vertical lines indicate Earth-Mars opposition dates.

Connecting Version II Semi-Cyclers

Aldrin proposed that we link the Version II semi-cyclers in the following way. First the Cycler Vehicle leaves Mars for Earth, encounters the Earth three times in 18 months, and then returns to Mars. The transits between Mars and Earth are about 6 months each. Upon Mars arrival, the vehicle then goes into a 3:2 resonance orbit with Mars (i.e. three vehicle revolutions during two Mars revolutions around the Sun). The time of flight (TOF) for this resonance orbit is 45 months, making the total time of flight about 76 months, or 3 synodic periods. After the final Mars arrival at the end of the resonance orbit, the cycle repeats, and the vehicle heads for Earth again. Since the entire sequence takes three synodic periods to complete, three vehicles are needed to guarantee that there will be a short TOF-transfer leg to each planet at every synodic opportunity.

We begin connecting Version II semi-cyclers by first duplicating the published result[10] with our trajectory propagator, STOUR. At the end of the MEEEM sequence, we place the vehicle into a 3:2 resonance orbit with Mars, and then attempt to return to Earth to begin the new cycle. In this way we are able to link two Version II semi-cyclers. Table 1 shows the summary of this trajectory.

The result shown in Table 1 is not optimized. We use our ballistic optimizer, MIDAS to minimize total ΔV. We also allow MIDAS to adjust event times, as well as adding and deleting maneuvers to improve the trajectory. Due to a software limitation in MIDAS, we cannot model three consecutive encounters with the same planet, thus we replace the middle three Earth flybys with two Earth flybys. However, due to the phasing of this trajectory, the neglected Earth flyby will still be present, and in fact cannot be ignored, as pointed out by Byrnes.[16] We also change the trajectory to reflect an Earth launch instead of a Mars launch. Using MIDAS, we are able to extend this trajectory to three cycles (about 17 years). Table 3 summarizes the optimized trajectory from MIDAS. The optimized trajectory has a total ΔV of 4.889 km/s. The V_∞ at Earth and Mars are relatively low. We believe that similar trajectories can be constructed for the other two vehicles required in the Version II cycler (to ensure transit opportunities at every synodic period). At this stage of our research, we consider Table 3 to be our best result and we will use it as our baseline case.

To model the ignored Earth flybys and further improve the result, we use our low-thrust trajectory optimizer, GALLOP to construct the trajectory summarized in Table 2. GALLOP does not have the flyby limitation that MIDAS has, thus we are able to model all of the Earth flybys. Comparing Tables 2 and 3, we see that even ignoring the Earth flybys in MIDAS, the trajectory summarized in Table 3 is still valid, as the missing Earth flybys can be achieved by "backflips" which will not significantly perturb the energy of the orbit. (For a discussion of the backflip orbit see Uphoff.[17]) The 2.55 km/s of total ΔV is very good by low-thrust standards, considering that an Earth-Mars-Ceres case with just one flyby and a 3-year TOF has a higher cumulative ΔV of 8.69 km/s.[15] Since the I_{sp} is 3000 seconds, the propellant mass expended by the Cycler is only 15 mt in 13 years. With GALLOP, we are also able to construct similar trajectories for the other two required vehicles.

We next present a metric for evaluating trajectories under consideration for a human transportation system to Mars.

Propellant Assessment of Baseline Cycler

Basic Assumptions

To assign a cost (metric) to a given Cycler, we calculate the required propellant mass. Design and development costs are not considered as we wish to assess the cost of *sustaining* a transportation system over a long period of time. Certain assumptions and restrictions are made to keep our estimation general enough to compare different scenarios (Cycler, Semi-Cycler, DRM-type[18] and others). The assumptions applied to our baseline analysis are as follows:

1.) The amount of mass being transported between Earth and Mars is 15 mt. This will be referred to as the "transport mass". We assume the same transport mass in either direction (i.e. Earth-Mars and Mars-Earth) to examine an "even trade" scenario (though we acknowledge that much more mass will be transported to Mars during an early colonization phase).

2.) The Cycler Vehicle carries three times the transport mass (45 mt) on its interplanetary routes. The added mass is termed "comfort mass" and accounts for anything that is required for interplanetary travel, but is not actually taken from one planet to the other (e.g. radiation shielding, structures, furniture etc.). Thus for our baseline, the comfort factor is f = 3. This comfort factor is estimated from mass values found in Refs. 9 and 19. In our study, a range of comfort factors is considered, since we find the value of f drives the cost metric.

3.) The Cycler Vehicle carries only enough propellant to achieve all necessary ΔV's until the next Taxi rendezvous.

4.) Propellant from Mars will be methane/oxygen. This propellant will be made from hydrogen sent from Earth on a low energy (Hohmann) transfer. One kilogram of this hydrogen is combined with the carbon dioxide in the Martian atmosphere to yield 16 kilograms of propellant. This estimate accounts for hydrogen boiloff losses during transfer.

5.) When a Cycler Vehicle is captured into a loose orbit about a planet, the periapsis will be 300 km above the planet's surface and the period will be one week. An orbit of this size and shape will stay well within the sphere of influence (SOI) of both Earth and Mars ($SOI_E \approx 145\ R_E$, $SOI_M \approx 170\ R_M$), so multi-body perturbations are assumed to not significantly alter this reference orbit. Thus the parking orbit will be modeled as a two-body problem. The orientation of this loose orbit is not computed and all ΔV values are computed at periapsis. In practice the orientation will need to be accounted for in more refined ΔV calculations.

6.) Mars Taxis are modeled as three-stage rockets that leave the surface and rendezvous with the Cycler Vehicle. One-third of the required ΔV is achieved by each stage.

7.) Earth Taxis are modeled as four-stage rockets. The first three stages will each achieve one-third of the ΔV necessary to leave Earth's surface and reach a loose orbit as defined in assumption 5. The final upperstage is required to rendezvous with the Cycler Vehicle on a hyperbolic trajectory.

8.) The upperstage of each Taxi will ride along with the Cycler Vehicle as a means of transporting mass from the Cycler Vehicle to the planet during an encounter. The booster stages will fall back towards the planet. Thus, there is no accumulation of Taxi material from one planet to the other.

9.) A portion or installment of the Cycler Vehicle is launched at each Earth-to-Mars leg. This is to account for maintenance or renovation of the Cycler Vehicles over an extended period of time. We assume that the Cycler Vehicle is completely renewed every five synodic periods.

10.) Cycler Vehicles are modeled as single-stage rockets.

11.) The I_{sp} assumed for Earth Taxis is 450 seconds (LOX, H_2), while the I_{sp} of Mars Taxis is 380 seconds (CH_4, O_2). Cycler Vehicles will use methane propellant with an I_{sp} of 380 seconds as well.

12.) The structure factor, $\mu_{struc} = m_{struc} / (m_{struc} + m_p)$ is 10% for Taxis and Cycler Vehicles.

13.) Taxis and Cycler Vehicles will aerobrake whenever needed at a planet. Fifteen percent of the payload mass will be used for aeroshells, i.e. $\mu_{as} = m_{as} / m_{transport} = 15\%$. Vehicles on full cyclic trajectories do not decelerate at a planet; therefore, they do not require aeroshells.

14.) Both Earth and Mars are assumed to be non-rotating spheres. Thus, no rotational velocity is added to taxi launches.

15.) The gravitational sources are modeled as a point masses.

Equations

The following fundamental equations allow us to estimate the amount of propellant that is required to sustain a transportation system between Earth and Mars. We find the change in velocity required by the Taxis to rendezvous with the Cycler Vehicle and the change in velocity required by the Cycler Vehicles to enter or leave a loose orbit about a planet from the following:

$$\Delta V_{taxi} = \sqrt{2\left(\frac{GM}{r_{surf}} + E_{cv}\right)} \qquad (1)$$

where E_{cv} is the specific energy of the Cycler Vehicle at rendezvous and is given by

$$E_{cv} = ½V_\infty^2 \text{ (hyperbola)}, \ E_{cv} = -\frac{GM}{2a_{loose}} \text{ (ellipse)} \qquad (2)$$

$$\Delta V_{loose} = \sqrt{\frac{2GM}{r_{peri}} + V_\infty^2} - \sqrt{GM\left(\frac{2}{r_{peri}} - \frac{1}{a_{loose}}\right)} \qquad (3)$$

Velocity losses such as drag, steering, gravity, etc. are neglected.

The “rocket equation” is used to determine mass fractions for a single stage

$$\mu_{stage} = \exp\left(\frac{V}{ngI_{sp}}\right) \qquad (4)$$

From Eq. 4, expressions for the initial mass and propellant mass are derived:

$$\mu_0 = \frac{m_0}{m_f} = \left[\frac{\mu_{stage}(1 - \mu_{struc})}{1 - \mu_{struc}\mu_{stage}}\right]^n \qquad (5)$$

$$\mu_p = \frac{m_p}{m_{pay}} = (\mu_0 - 1)(1 - \mu_{struc}) \qquad (6)$$

The payload mass on a Cycler Vehicle includes the transport mass, the aeroshell(s), the comfort mass, and any propellant required for future maneuvers. The Taxi payload is the transport mass plus an aeroshell and propellant to refuel the Cycler Vehicle. The propellant cost estimate is the same if a separate Taxi is used to refuel the Cycler Vehicle or if only one Taxi is used per rendezvous. Whenever propellant is a payload, the structure required to contain it (from μ_{struc}) is included.

Equation 6 demonstrates that the propellant mass is directly proportional to the payload mass. Using this property we may express the required propellant in terms of transport mass, then simply multiply this propellant mass fraction by the transport mass to calculate the value in mass units. For example, the propellant required by a Cycler Vehicle to perform a maneuver is

$$m_p = m_{transport} \cdot f \cdot (1 + \mu_{as}) \cdot \mu_{p-cv} \qquad (7)$$

where $\mu_{p\text{-}cv}$ is found using Eqs. 4, 5, and 6. Since this propellant reaches the Cycler Vehicle via a Taxi, the total Taxi propellant is

$$m_p = m_{transport} \cdot (1 + \mu_{as}) \cdot \left[1 + f \cdot \mu_{p-cv}\left(1 + \frac{\mu_{struc}}{1 - \mu_{struc}}\right)\right]\mu_{p-taxi} \qquad (8)$$

We note that $\mu_{struc} / (1-\mu_{struc}) = m_{struc} / m_p$. Thus the propellant mass required by both Cycler Vehicles and Taxis is directly proportional to the transport mass.

Baseline Cycler and Semi-Cycler Propellant Estimation

Propellant costs for the Version II Cycler and the Version II Semi-Cycler are calculated using the above assumptions. The results are summarized in Tables 3 and 4, respectively.

The "Cost per Synodic Period" of each estimate incorporates all of the vehicles necessary to complete a transfer from Earth to Mars and another transfer from Mars to Earth every synodic period (e.g. three vehicles for the Version II Cycler and two vehicles for the Version II Semi-Cycler). The other two vehicles required for the Version II Cycler are assumed to perform similarly to the one presented in Table 3 to give an estimate for the entire system.

The resulting costs of the two systems are remarkably similar, yet the patched Cycler is slightly more efficient than the Semi-Cycler. Launching a payload from Earth requires more propellant than launching from Mars due to the relatively strong gravity field (compare, for example, E-1 and M-3 in Table 3). However, the Mars-launch propellant cost is more than doubled to account for the transportation of hydrogen (from Earth to Mars) for methane production (on Mars), and becomes a considerable factor. For example, approximately 230 mt of propellant must be expended at Earth to launch enough hydrogen to create the 187.7 mt of methane/oxygen required at M-3, thus the M-3 propellant cost is more than doubled to about 420 mt (where the extra mass is accounted for in the total propellant value). In general, the midcourse corrections required by the patched Cycler are significantly less than the transport mass with the notable exception of DSM (Deep Space Maneuver) 5, while the Semi-Cycler ΔV costs are greater than the transport mass. The large trajectory correction (DSM5) seems to balance out the large Semi-Cycler Mars encounter costs, resulting in similar costs per synodic period.

Propellant Cost Analysis

We see that in the specific case of the Version II Semi-Cycler and patched Cycler, neither system provides a significant advantage in propellant cost; however, it is informative to see how different transportation systems compare in general. We now investigate the role that V_∞, the comfort factor, and the magnitude of trajectory-correction maneuvers have on the relative cost of cycling systems. Moreover, we extend our analysis to other types of transportation systems.

In addition to Cyclers and Semi-Cyclers, we examine a NASA DRM-type[18] mission (our version is only concerned with whether the comfort mass is launched or placed in a parking orbit, not the specifics of the DRM), a system that incorporates parking orbits at both Earth and Mars (termed Double Park), and a system with Mars flybys and a parking orbit at Earth (Reverse Semi-Cycler). All of these systems follow the previously mentioned set of assumptions (regarding Taxis, loose orbits, etc.) and are distinguished by the role of the transport vehicle at a planetary encounter. Since the DRM type of mission launches a new comfort mass each mission, it does not need to aerobrake at the Earth return encounter. Table 5 provides a summary of each system.

While no actual trajectories will be presented for the Double Park and Reverse Semi-Cycler class missions, we expect that the Double Park trajectories will have much freedom in terms of Earth-Mars phasing because no gravity assists are required (as in NASA's DRM), while Reverse Semi-Cyclers will have phasing restrictions similar to those of full cyclic trajectories since Mars is a poor gravity-assist body. Our analysis provides a preliminary estimate of the propellant advantages and disadvantages of these systems.

To examine the effects of the comfort factor and V_∞, f is varied from one to five and V_∞ is varied from 3 to 10 km/s. A comfort factor of one has no amenities and may not lead to a successful mission, while a comfort factor of five may be considered somewhat extravagant. The lowest energy (Hohmann) transfer has a V_∞ of below 3 km/s at Earth or Mars and is thus the lower V_∞ bound. The transport mass and V_∞ at Earth and Mars are assumed to be equal. It is also assumed that the only transportation system that will require significant mid-course trajectory corrections is the Cycler. These corrections are modeled as a single ΔV with a magnitude of 300 m/s. The cost of a given system is calculated on a per synodic period basis, where a shipment of mass from Earth to Mars and a separate shipment from Mars to Earth will occur each synodic period. This propellant cost is normalized by $m_{transport}$, since the propellant mass is directly proportional to transport mass.

The regions where a particular transportation system is cheaper than the other four are presented in the f-V_∞ plane in Fig. 2, where the regions are separated by a solid line.

All five transportation systems are evaluated to generate Fig. 2, however only Cyclers and Semi-Cyclers provide the cheapest method of transporting a given mass from Earth to Mars and vice-versa.

Moreover, we note that as the comfort mass and V_∞ increase, full cyclic systems are always the best performer.

This arises because the cost of accelerating the Cycler Vehicle out of Mars' gravity well increases as the Cycler Vehicle mass (dependent on f) increases and the ΔV (dependent on V_∞) increases. The propellant cost (m_p / $m_{transport}$) at the nominal point (f = 3 and V_∞ = 5 km/s) are provided in Table 6.

The main cost driver in these systems is the amount of mass that must be accelerated. Since the transport mass must be launched from the surface of a planet for each system, the comfort mass leads to the largest variation in cost among these systems. Full cyclic systems only require the transport mass to be accelerated to reach another planet, while the semi-cycling systems have the additional cost of accelerating the comfort mass at one of the planets. The Double Park system must accelerate the comfort mass at both planets, and finally, the DRM class mission must accelerate the comfort mass from Earth's surface in addition to the propellant required to accelerate the comfort mass out of a loose Mars orbit. Consequently the relative rank of these systems is directly affected by how much the comfort mass must be accelerated out of a gravity well.

The data in Tables 3 and 4 correspond to the point in Fig. 2 where f equals three and V_∞ is around 4.5 km/s, which is clearly most efficient for a full Cycler. However, in Tables 3 and 4, the Cycler and the Semi-Cycler have very similar propellant costs per synodic period (1,154 mt vs. 1,177 mt, respectively). The reason the Cycler of Table 3 is only slightly better than the Semi-Cycler in Table 4 (rather than significantly better as predicted by Fig 2.) is that this particular Cycler expends a ΔV of 4.889 km/s (which corresponds to 1.849 km/s per synodic period for the three required Cycler Vehicles). In Fig. 2, we assume a trajectory-correction-maneuver budget of only 300 m/s. Incidentally, the Aldrin Cycler[5] uses about 0.54 km/s of ΔV per synodic period, which is a relatively small maneuver, but this cycler has high V_∞ (i.e. 7 to 12 km/s at Mars). From Fig. 2, we know that an Aldrin Cycler is more efficient than an Aldrin Semi-Cycler would be (for values of f even slightly greater than one) due to its high V_∞.

Since the propellant required to launch something from Earth's surface is generally the largest cost, the potential for significant savings exists if less mass is required to leave the surface of Earth. While transport mass launches are required to sustain a transportation system, not all of the propellant used in Earth's vicinity is required to originate at Earth. For example, fuel produced at Mars (methane/oxygen) may be transported to Earth orbit via a low energy transfer and used in the upper stages of Cycler Vehicles to escape Earth's gravity. This system would require a separate refueling Taxi to leave Mars with enough time to reach Earth before a transport mass launch so that there will be propellant to leave Earth's vicinity. The propellant properties of this system are presented in Fig. 3 and Table 7.

From Table 7 we note that all of the systems have a discernable decrease in cost, but the Reverse Semi-Cycler, Double Park and DRM-type systems gain more savings than Cyclers and Semi-Cyclers from using Mars propellant. This savings is the result of launching the propellant required to leave a loose Earth orbit from Mars instead of Earth, thereby bypassing the stronger gravity field. In this case, semi-cycling systems (including the Reverse Semi-Cycler) become the most economical method as the Cycler Vehicle mass decreases. However for comfort factors above 2, full cyclic systems are consistently the best alternative.

While primarily using Mars-based propellant can result in significant savings, it is not guaranteed that we will be able to produce propellant on Mars. In this case, all of the propellant will need to come from Earth. To be as efficient as possible only propellant required at Mars' surface will be launched there (i.e. propellant used by a Cycler Vehicle will be carried from Earth) and an H_2/LOX mix will be used (where 15% of the propellant is assumed to boil off before it is used). The results are presented in Fig. 4 and Table 8.

As expected, the propellant cost of this scenario is significantly greater than the other cases as much more propellant must be launched from Earth's surface and transported to Mars. The cost of launching transport mass from the surface of Mars becomes more significant, causing the cost savings of sending mass to a Martian parking orbit versus sending mass to a hyperbolic trajectory to be magnified. The result is a larger Semi-Cycler region in Fig. 4. However, as the comfort mass or V_∞ increases, the cost of accelerating the Cycler Vehicle out of a parking orbit becomes so large that the Cycler system again becomes the most efficient transportation system.

Nuclear propulsion is emerging as a viable, extremely efficient alternative. The specific impulse that nuclear engines could achieve is in the upper hundreds of seconds (we use 900 s). However, all of the nuclear propellant must come from Earth. We examine the effects of using nuclear propulsion for the Cycler Vehicles; the results are given in Fig. 5 and Table 9.

Table 3: Baseline Cycler propellant cost[a] (from MIDAS)

Encounter	Date (mm/dd/yyyy)	V_∞ or ΔV (km/s)	Prop. Mass (mt[b])	TOF (Days)	Altitude (km)
E-1	1/23/2016	5.177	553.0		
M-2	9/26/2016	4.854	aerobrake	247	200
DSM 1	**7/9/2017**	**0.001**	**0.01**		
M-3	7/1/2020	4.855	187.7	1374	2415
DSM 2	**11/8/2020**	**0.020**	**0.30**		
E-4	1/22/2021	5.133	aerobrake	205	20050
DSM 3	**5/7/2021**	**0.577**	**8.06**		
E-5	7/27/2022	5.515	1,203	551	200
E-5 DV	**7/27/2022**	**0.252**	**8.24**		
DSM 4	**11/22/2022**	**0.115**	**3.55**		
M-6	4/18/2023	3.474	aerobrake	265	200
M-6 DV	**4/18/2023**	**0.070**	**2.10**		
DSM 5	**3/7/2024**	**1.966**	**45.32**		
DSM 6	**1/30/2026**	**0.803**	**11.67**		
M-7	10/20/2026	4.269	207.6	1281	200
DSM 7	**3/4/2027**	**0.572**	**9.10**		
E-8	6/22/2027	3.906	aerobrake	245	200
DSM 8	**8/25/2028**	**0.438**	**5.97**		
E-9	12/20/2028	3.298	458.9	547	27061
M-10	8/8/2029	4.152	aerobrake	231	200
M-11	5/13/2033	4.152	108.7	1374	200
DSM 9	**8/19/2033**	**0.075**	**0.96**		
E-12	11/23/2033	6.055	aerobrake	194	
Total ΔV =4.889 km/s		Total Propellant =	3,460 mt[c]		
	Cost per Synodic Period =		**1,154 mt**		

[a] Close passes of the Earth are expected between E-4 and E-5, and E-8 and E-9, but are not modeled here.
[b] Metric tons (mt).
[c] Cost includes 646.2 mt of fuel to send hydrogen to Mars.

Table 4: Version II Semi-Cycler propellant cost

Vehicle 1						
Encounter	**Date**	**V_∞**	**ΔV (km/s)**	**S/C Propellant (mt[a])**	**Taxi Prop. (mt)**	**TOF (days)**
M1	2/21/2016	3.27	1.07	17.87	120.5	
E2	9/24/2016	5.18			aerobrake	235
E3	9/25/2017	5.18			b	1 year
E4	3/26/2018	5.18			573.6	½ year
M5	10/12/2018	3.69	1.32	aerobrake	aerobrake	203
Vehicle 2						
Encounter	**Date**	**V_∞**	**ΔV (km/s)**	**S/C Propellant (mt)**	**Taxi Prop. (mt)**	**TOF (days)**
M1	4/25/2018	6.10	3.02	75.00	326.7	
E2	11/26/2018	5.26			aerobrake	190
E3	11/26/2019	5.26			b	1 year
E4	5/27/2020	5.26			579.0	½ year
M5	12/16/2020	4.17	1.62	aerobrake	aerobrake	217
Total Cost = 2,353 mt[c]			**Cost per Synodic Period =**		**1,177 mt**	

[a] Metric tons (mt).
[b] No Taxi rendezvous occurs on this flyby.
[c] Accounts for 660.5 mt of fuel to send hydrogen to Mars.

Table 5: Summary of Earth Mars transportation systems

System	Earth Encounter	Mars Encounter
Cycler	Flyby	Flyby
Semi-Cycler	Flyby	Parking Orbit
Reverse Semi-Cycler	Parking Orbit	Flyby
Double Park	Parking Orbit	Parking Orbit
DRM Type	Launch/Aerobrake	Parking Orbit

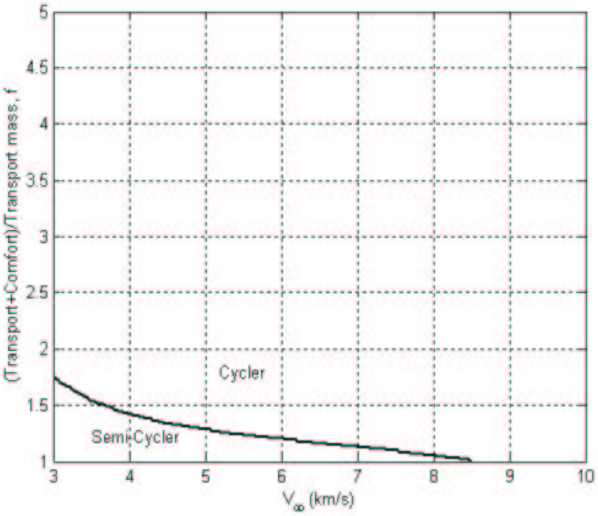

Fig. 2: Optimal transportation system regions.

Table 6: Normalized[a] Propellant cost of nominal systems

System	Cycler	Semi-Cycler	Reverse Semi-Cycler	Double Park	DRM Type
Cost	60.73	76.07	72.46	92.6	120.7

[a] Propellant cost normalized by transport mass.

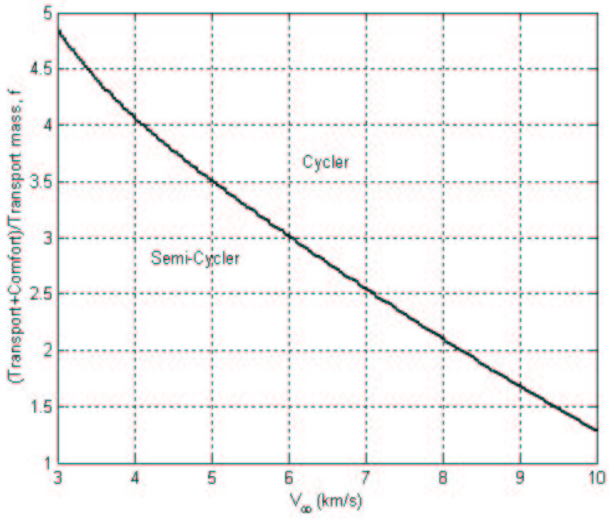

Fig. 4: Optimal systems using Earth propellant only.

Table 8: Normalized propellant cost for Earth propellant system (f = 3, $V_\infty = 5$ km/s)

System	Cycler	Semi-Cycler	Reverse Semi-Cycler	Double Park	DRM Type
Cost	175.1	164.9	182.2	176.5	201.8

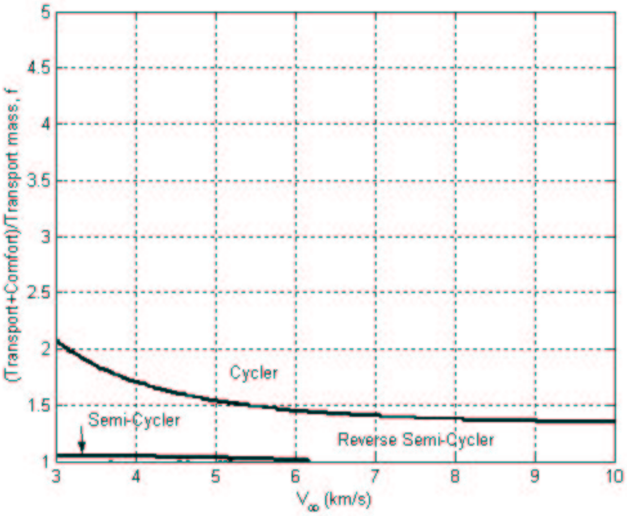

Fig. 3: Optimal systems with Martian propellant transported to Earth.

Table 7: Normalized propellant cost for Martian propellant system (f = 3, $V_\infty = 5$ km/s)

System	Cycler	Semi-Cycler	Reverse Semi-Cycler	Double Park	DRM Type
Cost	57.95	74.06	63.23	83.43	111.5

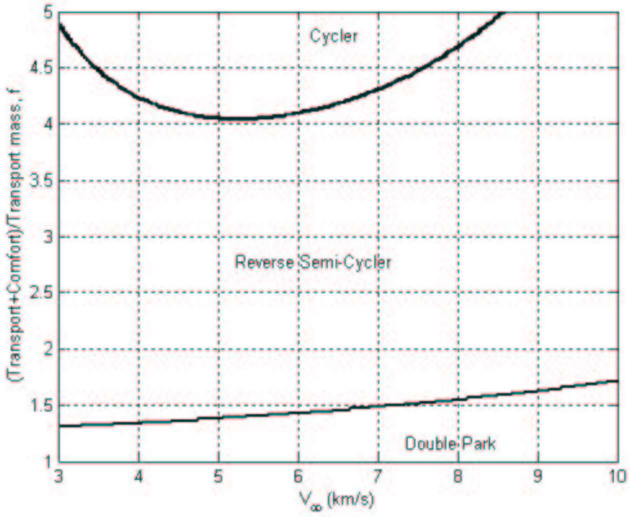

Fig. 5: Optimal transportation systems using nuclear propulsion.

Table 9: Normalized propellant cost with nuclear propulsion (f = 3, $V_\infty = 5$ km/s)

System	Cycler	Semi-Cycler	Reverse Semi-Cycler	Double Park	DRM Type
Cost	57.40	71.93	55.65	67.91	96.67

Table 10: Normalized propellant cost for non-aerobraking systems (f = 3, $V_\infty = 5$ km/s)

System	Cycler	Semi-Cycler	Reverse Semi-Cycler	Double Park	DRM Type
Cost	60.60	144.7	94.45	185.2	166.8

The main benefit of nuclear propulsion is a significant drop in cost to accelerate a large amount of mass from a loose orbit around Earth. The savings is smaller at Mars because the propellant must be shipped there.

Because the propellant is different than the previous scenarios the structure factor μ_{struc} may change (but in this study we keep it at 10%), and the comfort factor (f) should be increased somewhat to account for the added mass of a nuclear engine. Because nuclear engines are assumed to be more massive than purely chemical engine, they are not used for the Cycler or Semi-Cycler Taxi upper stages at Earth. (The idea of a Taxi is to bring the transport mass to an interplanetary vehicle using the smallest payload possible.) If nuclear engines are used on these upper stages then Cycler systems will be the cheapest alternative for a larger range of comfort factors as V_∞ increases (i.e. the top curve in Fig. 5 would continue to slope down instead of turning up towards the right side of the figure). We again see the trend of systems incorporating parking orbits becoming more efficient as comfort mass decreases leading to lighter Cycler Vehicles.

Next we examine the effects if aerobraking is deemed an infeasible way of decelerating the Cycler Vehicles. The transport mass is still assumed to aerobrake as a way of landing the transport mass on a planet's surface, however. Refueling of the Cycler Vehicles will occur evenly as specified in assumption 3. The nominal point values are presented in Table 10. Due to the added cost of decelerating vehicles using chemical propulsion, a full cyclic system will be the optimal choice for any comfort factor and V_∞ above 3 km/s.

The Cycler system clearly has the lowest cost as the other systems increase dramatically in cost to decelerate the comfort mass. The propellant costs of this scenario depend not only on the number of maneuvers involving the comfort mass, but also the amount of propellant that is essentially added cargo during a maneuver. For example, the propellant required by a Semi-Cycler to enter a Mars loose orbit must be accelerated from Earth's vicinity while the only thing to leave Earth using a Reverse Semi-Cycler is the transport mass. This causes a significant discrepancy due to Earth's relatively large gravitational field. The propellant savings of aerobraking is seen to outweigh the complexity of decelerating a massive object using an aeroshell.

Summary of Transportation System Trades and Conclusions

A general rule for any transportation scheme is to accelerate the smallest amount of mass possible. Consequently, full cyclic systems consistently provide the cheapest method of sustaining a transportation system between Earth and Mars because the least amount of mass must work against a gravitational field. More specifically, the comfort mass (regardless of its chosen value) is never accelerated out of a planet's gravity well, which tends to provide Cyclers with a significant advantage. However, Cyclers are not always the best alternative. Systems incorporating parking orbits become more efficient as the added comfort mass and/or approach velocity at planetary encounters decrease, i.e. as less mass is accelerated. Moreover as the midcourse corrections to sustain a full cyclic trajectory increase, Cycling systems become a less attractive alternative. The relative effect of this added cost is dependent on the scenario, but a cycling system will still require the least propellant for large comfort factors or large V_∞.

There are several factors besides propellant cost to consider when examining the best method of transporting mass between Earth and Mars. For example, Cyclers often provide the cheapest alternative, but are also the most complicated in terms of rendezvous (hyperbolic encounters) and require the most precision in encounter dates. Other, more expensive, alternatives such as the Double Park or DRM scenarios achieve all mass transfers near a planet in a parking orbit, and if a transport launch is not possible on a given day, then these systems will not be affected by delays as severely as a Cycler would. Moreover, modification of the time of flight (TOF) for Cyclers often requires a significant change in the trajectory requirements (ΔV, V_∞, etc.), whereas a balance between TOF and V_∞ is more easily attained for other, less restrictive, systems.

Finally, all of the previously discussed transfer costs are to sustain a *previously established* transportation system. The design and development costs are not considered, but are important to initiate a human presence on Mars. Our systems are better imagined as part of the evolution of humankind's first efforts to sustain a presence on Mars. For example, a DRM type mission may be the best alternative for the first few missions to Mars, but the propellant costs can be significantly reduced if the comfort mass is put into orbit around Earth after the return trip, i.e. if it evolves into a Double Park system. From there, semi-cyclic and full cyclic trajectories are established by adding planetary flybys and less propellant must be produced. The result suggests a safe, comfortable, and cost effective method for the routine exploration and development of Mars.

Acknowledgements

This work has been sponsored in part by the Jet Propulsion Laboratory, California Institute of Technology under Contract Number 1223406 (G. T. Rosalia, Contract Manager and Dennis V. Byrnes, Technical Manager). We are grateful to Neville I. Marzwell for his support.

References

1. Hollister, W. M, "Castles in Space," *Astronautica Acta,* Vol. 14, 1969, pp. 311-316.
2. Rall, C. S. and Hollister, W. M, "Free-Fall Periodic Orbits Connecting Earth and Mars," AIAA Paper No 71-92, AIAA 9th Aerospace Sciences Meeting, New York, NY, Jan. 25-27, 1971.
3. Friedlander, A. L., Niehoff, J. C., Byrnes, D. V., and Longuski, J. M., "Circulating Transportation Orbits Between Earth and Mars," AIAA Paper 86-2009, AIAA/AAS Astrodynamics Conference, Williamsburg, VA, Aug. 18-20, 1986.
4. Aldrin, B., "Cyclic Trajectory Concepts," SAIC presentation to the Interplanetary Rapid Transit Study Meeting, Jet Propulsion Laboratory, Oct. 28, 1985.
5. Byrnes, D. V., Longuski, J. M., and Aldrin, B., "Cycler Orbit Between Earth and Mars," *Journal of Spacecraft and Rockets,* Vol. 30, No. 3, May-June 1993, pp. 334-336.
6. Hoffman, S. J., Friedlander, A. L., and Nock, K. T., "Transportation Node Performance Comparison for a Sustained Manned Mars Base," AIAA Paper 86-2016, AIAA/AAS Astrodynamics Conference, Williamsburg, VA, Aug. 18-20, 1986.
7. Bishop, R. H., Byrnes, D. V., Newman, D. J., Carr, C. E., and Aldrin, B., "Earth-Mars Transportation Opportunities: Promising Options for Interplanetary Transportation," AAS Paper 00-255, The Richard H. Battin Astrodynamics Conference, College Station, TX, Mar. 20-21, 2000.
8. Nock, K. T, "Cyclical Visits to Mars via Astronaut Hotels," Phase I Final Report, NASA Institute for Advanced Concepts, Universities Space Research Association Research Grant 07600-049, Nov. 30, 2000.
9. Nock, K. T., and Friedlander, A. L., "Elements of a Mars Transportation System," *Acta Astronautica*, Vol. 15, No. 6/7, pp. 505-522, 1987.
10. Aldrin, B., Byrnes, D., Jones, R., and Davis, H., "Evolutionary Space Transportation Plan for Mars Cycling Concepts," AIAA Paper 2001-4677, Albuquerque, NM, Aug. 2001.
11. Rinderle, E. A., "Galileo User's Guide, Mission Design Systems, Satellite Tour Analysis and Design Subsystem," Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, JPL D-263, July 1986.
12. Sauer, Jr., C. G., "MIDAS: Mission Design and Analysis Software for the Optimization of Ballistic Interplanetary Trajectories," *The Journal of the Astronautical Sciences,* Vol. 37, No. 3, July-Sept. 1989, pp. 251-259.
13. Petropoulos, A. E., "A Shape-Based Approach to Automated, Low-Thrust, Gravity-Assist Trajectory Design," Ph.D. Thesis, School of Aeronautics and Astronautics, Purdue University, West Lafayette, May 2001.
14. Sims, J. A. and Flanagan, S. N, "Preliminary Design of Low-Thrust Interplanetary Missions," AAS Paper 99-338, AAS/AIAA Astrodynamics Specialist Conference, Girdwood, AK, Aug. 16-19, 1999.
15. McConaghy, T. T., Debban, T. J., Petropoulos, A. E., and Longuski, J. M., "An Approach to Design and Optimization of Low-Thrust Trajectories with Gravity Assists," AAS Paper 01-468, AAS/AIAA Astrodynamics Specialists Conference, Quebec City, QC, Canada, July 30-Aug. 2, 2001.
16. Byrnes, D., personal communication, Oct.-Nov. 2001.
17. Uphoff, C., "The Art and Science of Lunar Gravity Assist," AAS Paper 89-170, AAS/GSFC International Symposium, Greenbelt, MD, Apr. 1989.
18. Hoffman, S. J. and Kaplan, D. I., eds., "Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team," NASA SP 6107, 1997.
19. Aldrin, B., Byrnes, D., Jones, R., and Davis, H., Thangavelu, M., "Evolutionary Space Transportation Plan for Mars Cycling Concepts," ShareSpace Foundation Final Report, NASA/JPL Contract No. 1230398, Oct. 2001.