Cost-Performance Parametrics for Transporting Small Packages to the Mars Vicinity

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Why Small Packages to Mars?

• A permanent presence on Mars will be a logistical challenge

• Arriving mass on continual basis is needed during build-up and assembly phase to augment the delivery of large/mid-size elements
  • In addition to seven (7) heavy lift missions, many smaller deliveries required:
    • 15-20 t = 7 flights
    • 10-15 t = 14 flights
    • 5-10 t = 7 flights
    • <5 t = 87 flights
  • Outfitting and resupply needs as build-up occurs
  • Low cost, low mass services: resupply, imaging, comm/navigation

• Arriving mass on continual basis is needed during sustainment
  • Much smaller mass throughput required during sustainment than build-up
  • Critical spares, commodities, components, and equipment—often driven by unplanned events and unknowns
  • Frequency often critical need—will a 2-year dwell between critical supplies be acceptable?

• Standardized packaging/containerization
  • Starts with the small standard shipping packages and aggregates to the larger shipping containers
Example Mars Surface Facility Masses (Metric Tons)
Example Earth-Mars Direct Transit Modes
(Earth/Lunar distant aggregation methods also under review, not covered in this initial investigation)

1. Direct Transfer
   (All-up Single launch)

2. LEO Parking/Departure

3. LD-HEO, High Frequency Accumulation
   (Focus of initial investigation)

Mars Vicinity Orbit
Mars Vicinity Way Point
(10-sol)
Lunar Distant Departures & Way Points (e.g., LD-HEO)
Lower ΔV to Mars
Typical plot of total $\Delta V$ (km/s) for impulse case Mars transits from LD-HEO to 10-sol Mars orbit (2034-2035)
Plots of total ΔV (km/s) for impulse case Mars transits from LD-HEO to 10-sol Mars orbit (2017-2035)
Transit System Assumptions (Initial Investigation)

<table>
<thead>
<tr>
<th>TRANSIT SPACECRAFT - CHEMICAL</th>
<th>value</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel</td>
<td>MMH</td>
<td></td>
</tr>
<tr>
<td>Oxidizer</td>
<td>NTO</td>
<td></td>
</tr>
<tr>
<td>Isp</td>
<td>315s</td>
<td></td>
</tr>
<tr>
<td>Mass ratio</td>
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<tr>
<td>Propellant mass fraction</td>
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<tr>
<td>Engine mass fraction</td>
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<td>Fuel tank mass fraction</td>
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<tr>
<td>Oxidizer tank mass fraction</td>
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<td>Structural mass fraction</td>
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<td>Dry mass fraction</td>
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<td>Payload mass fraction</td>
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<table>
<thead>
<tr>
<th>TRANSIT SPACECRAFT - ELECTRIC</th>
<th>value</th>
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<tbody>
<tr>
<td>Propellant</td>
<td>Xe</td>
<td></td>
</tr>
<tr>
<td>Isp</td>
<td>3,000s</td>
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<tr>
<td>Propellant mass fraction</td>
<td>0.2749</td>
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<tr>
<td>Propulsion Power/Mass</td>
<td>2.7000</td>
<td>W/kg</td>
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<tr>
<td>Thruster efficiency</td>
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<tr>
<td>PPU and Power Efficiency</td>
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<td>Propulsion alpha</td>
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<td>kg/W</td>
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<tr>
<td>Solar power alpha</td>
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<td>kg/W</td>
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<tr>
<td>Duty cycle (correction)</td>
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<tr>
<td>Structural mass fraction</td>
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<tr>
<td>Dry mass fraction</td>
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<table>
<thead>
<tr>
<th>DRY MASS TABLE</th>
<th>value</th>
<th>units</th>
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<tbody>
<tr>
<td>Fuel Tank characteristics</td>
<td>Density</td>
<td>875 kg/m³</td>
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<tr>
<td>Safety factor</td>
<td>4</td>
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</tr>
<tr>
<td>Material specific density</td>
<td>4 kg/m³/Mpa</td>
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</tr>
<tr>
<td>MEOP pressure</td>
<td>1.8 Mpa</td>
<td></td>
</tr>
<tr>
<td>Propellant fraction %</td>
<td>37.74 pct (%)</td>
<td></td>
</tr>
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</table>

| Oxidizer Tank characteristics | Density | 1443 kg/m³ |
| Safety factor                 | 4       |       |
| Material specific density     | 4 kg/m³/Mpa |
| MEOP pressure                 | 1.8 Mpa |       |
| Propellant fraction %         | 62.26 pct (%)| |
| Structural coefficient, eS   | 0.04    |       |

- Spacecraft sizing approach used simple characteristics/mass fraction
- LEO to LD-HEO scale factor of 30% found across launch vehicle classes
- Key Isp parameters were 315 s (chemical); 3,000 s (electric)
Example plot of chemical system departure and arrival masses across two synodic cycles (nano-micro launch class delivery case)

![Graph showing mass over time from initial departure to Mars orbit.](image)
Constant thrust orbital transfer for electric propulsion case in optimal (left) and minimal payload (right) transfers.

- - - - Vehicle + p/l mass in HEO

<table>
<thead>
<tr>
<th>Months from Initial Departure (8/20/2034)</th>
<th>Mass, kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>50</td>
</tr>
<tr>
<td>6</td>
<td>100</td>
</tr>
<tr>
<td>9</td>
<td>150</td>
</tr>
<tr>
<td>12</td>
<td>200</td>
</tr>
<tr>
<td>15</td>
<td>250</td>
</tr>
<tr>
<td>18</td>
<td>300</td>
</tr>
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Arrivals not fully synchronous with departures.
Affordability and flight rate capability parametric plots under investigation
Early results for high-frequency, variable capacity Mars transits from LD-HEO

<table>
<thead>
<tr>
<th>CHEMICAL PROPULSION MARS TRANSITS</th>
<th>Nano-MicroLauncher</th>
<th>Small Launcher</th>
<th>Medium Launcher</th>
<th>Heavy Launcher</th>
<th>Super Heavy Launcher</th>
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<tr>
<td>ETO Launch Vehicle Capacity to LEO 28.5° (kg/ft)</td>
<td>100</td>
<td>1,000</td>
<td>10,000</td>
<td>25,000</td>
<td>100,000</td>
</tr>
<tr>
<td>Assumed Avg Flt Rate Capacity per veh type (Flts/syn cycle)</td>
<td>26</td>
<td>19</td>
<td>11</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>Spacecraft + Payload (kg/ft to LD-HEO w/ 0.313 fraction)</td>
<td>31</td>
<td>313</td>
<td>3,130</td>
<td>7,825</td>
<td>31,300</td>
</tr>
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<td>Cumulative Delivery to LD-HEO (kg/syn cycle to LD-HEO)</td>
<td>407</td>
<td>4,069</td>
<td>30,584</td>
<td>51,408</td>
<td>71,190</td>
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<tr>
<td>Estimated LEO CPK High Average ($/kg)</td>
<td>$200,000</td>
<td>$63,240</td>
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<td>$12,640</td>
<td>$6,320</td>
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| Available Monthly Mars Transits (opportunities/syn cycle) | 20 | 20 | 20 | 20 | 20 |
| Launcher-Capable Transit Opportunities (xfers/syn cycle) | 26 | 19 | 11 | 8 | 3 |
| Transferred at Optimum Alignment (kg/transit) | 18 | 175 | 1,754 | 4,387 | 17,546 |
| Mars 10Sol Accumulation Rate (kg/syn cycle) | 350 | 3,325 | 19,294 | 35,093 | 52,638 |
| Estimated Transit CPK High Average ($/kg) | $747,879 | $236,500 | $74,788 | $47,300 | $23,650 |
| Estimated Transit CPK Low Average ($/kg) | $134,397 | $42,500 | $13,440 | $8,500 | $4,250 |
| Cost-per Transit (expendable) High ($/flt) | $23,400,000 | $74,020,000 | $74,020,000 | $370,120,000 | $1,896,000,000 |
| Cost-per Transit (expendable) Low ($/flt) | $4,200,000 | $13,300,000 | $13,300,000 | $66,510,000 | $350,930,000 |
| Derived LD HEO CPK-High ($/kg) | $638,900 | $201,900 | $71,900 | $49,100 | $26,600 |
| Derived LD HEO CPK-Low ($/kg) | $170,600 | $53,900 | $19,200 | $13,100 | $7,100 |

| Mars Orbit Transfers (10-sol to 1-sol) | - | 19 | 11 | 8 | 3 |
| M10-sol to 1-sol circularization loss | - | 0.035 | 0.035 | 0.035 | 0.035 |
| M1Sol Accumulation Rate (kg/syn cycle) | - | 3,209 | 15,261 | 27,758 | 41,636 |
| Mars Landings | - | 1.22 | 1.22 | 1.22 | 1.22 |
| Mars 1-sol to surface transfer loss | - | 2,630 | 15,261 | 27,758 | 41,636 |
| Surface Facility Build-up Rate w/ 22% landing loss (kg/syn cycle) | - | - | - | - | - |

1 2034/35 synodic cycle opportunities
Variety of size classes to construct and sustain large space facilities

In-Space Facility Assembly Campaign (ISS, 1998-2011)

Mars Facility Assembly/Logistics Campaign

Assembly Emphasis

Delivery Capacity, Metric Tons

Cumulative Mass at Mars, MT

Electric propulsion results shown
Conclusions

• Prospects promising for smaller class systems using higher frequency full synodic cycle deliveries
• Could augment assembly & logistics; will explore future packaging and shipping options
• Transit time and trajectory optimization needed
• Methods of varying cadence/distribution of departures and arrivals should be investigated
• Size class roles/options need further investigation to maximize logistical deliveries by shipment size
• Need more data on support system functions and their logistics masses/rates required
• Investigation of different concepts for lunar and Mars vicinity waypoint operations—e.g., aggregated shipments
• Further investigation of affordability analysis warranted (i.e., from Earth-Surface to Mars surface)
• Commercial/economic potential—service sector implications of packaged cargo delivery rather than monolithic designs (i.e., cost of service to one player is the revenue to another)
• Package deliveries to Mars—small and large—may be enabling to support ambitious plans