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

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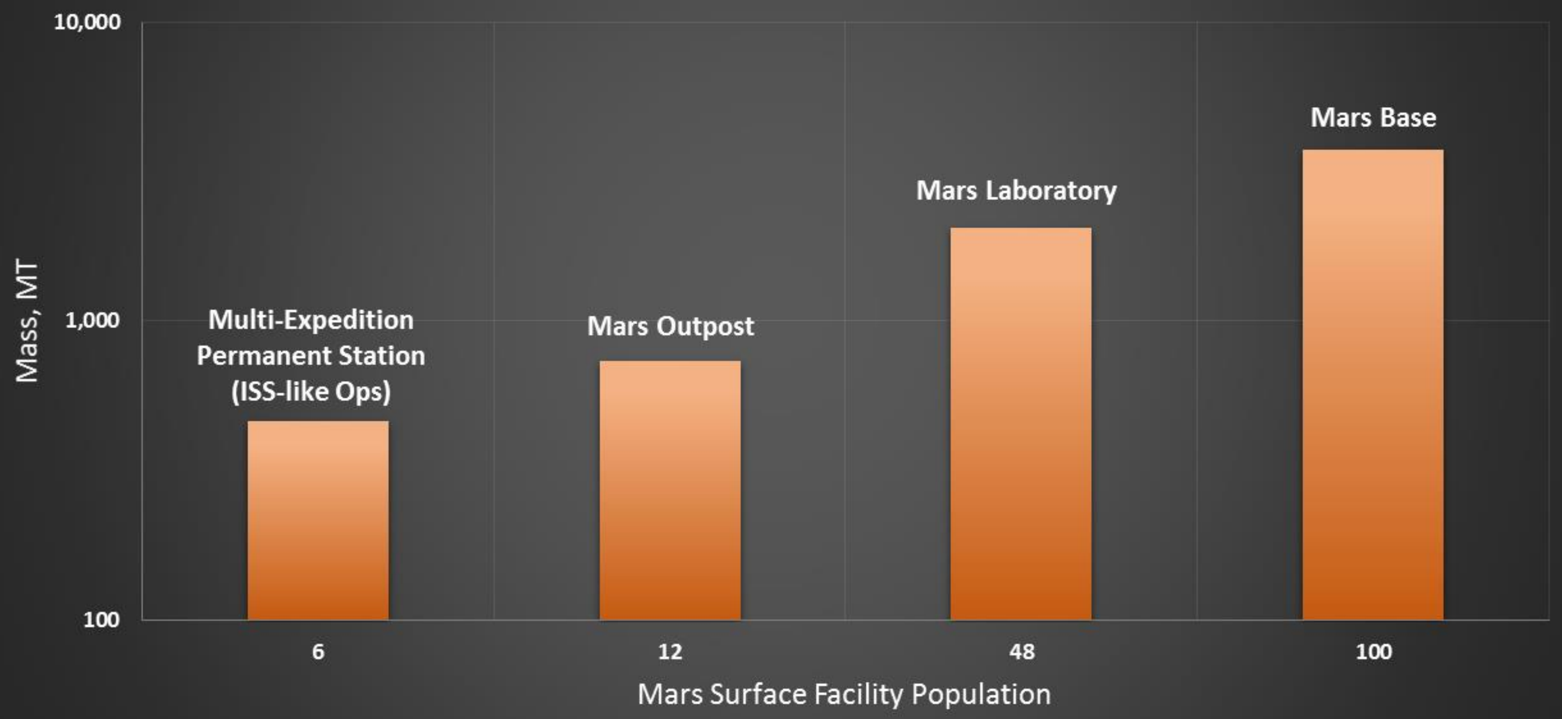
Why Small Packages to Mars?

- **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**

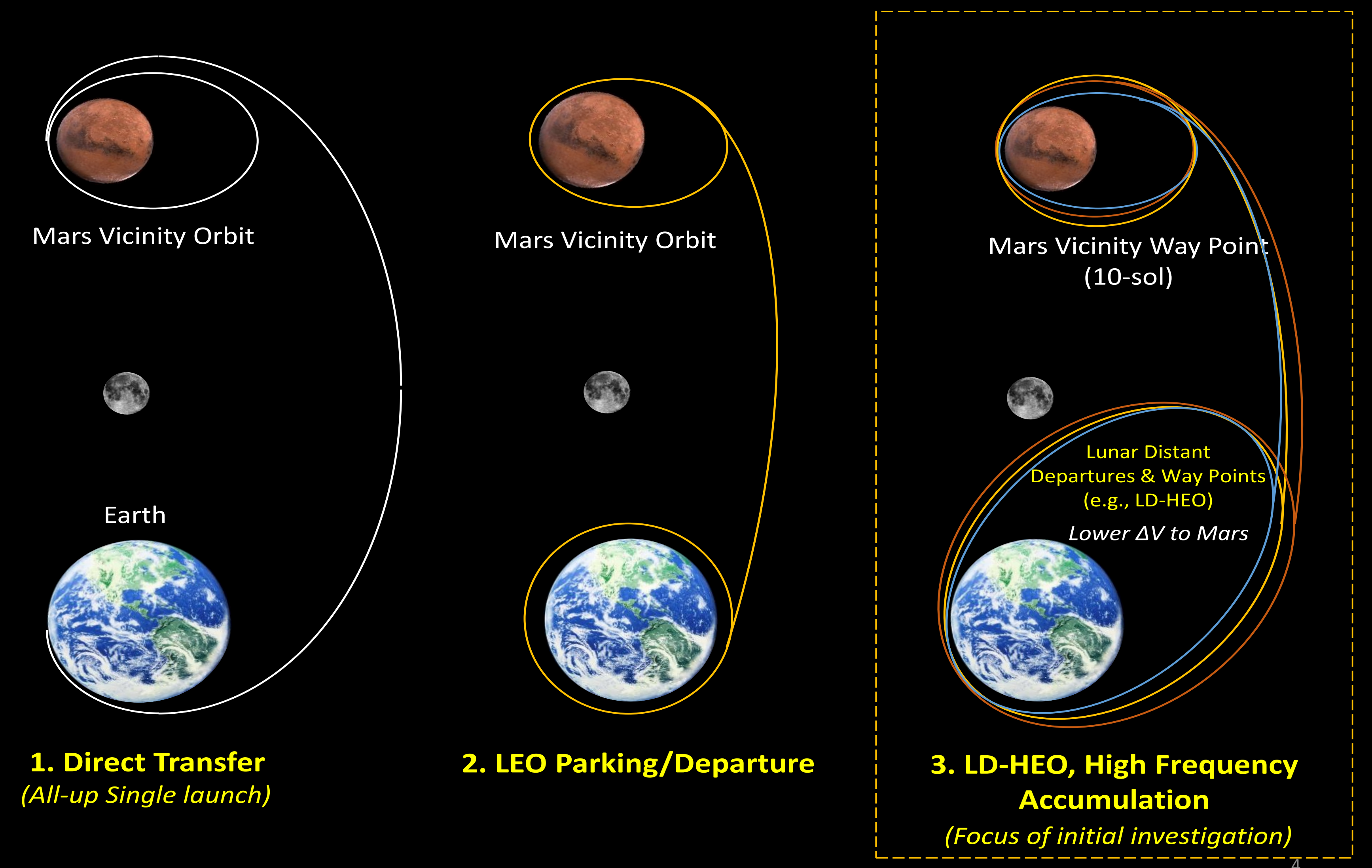
Example Mars Surface Facility Masses (Metric Tons)

[from Koelle, H. H., *Lunar Base Quarterly*, vol. 11, No. 2, April 2003, Berlin, DE]

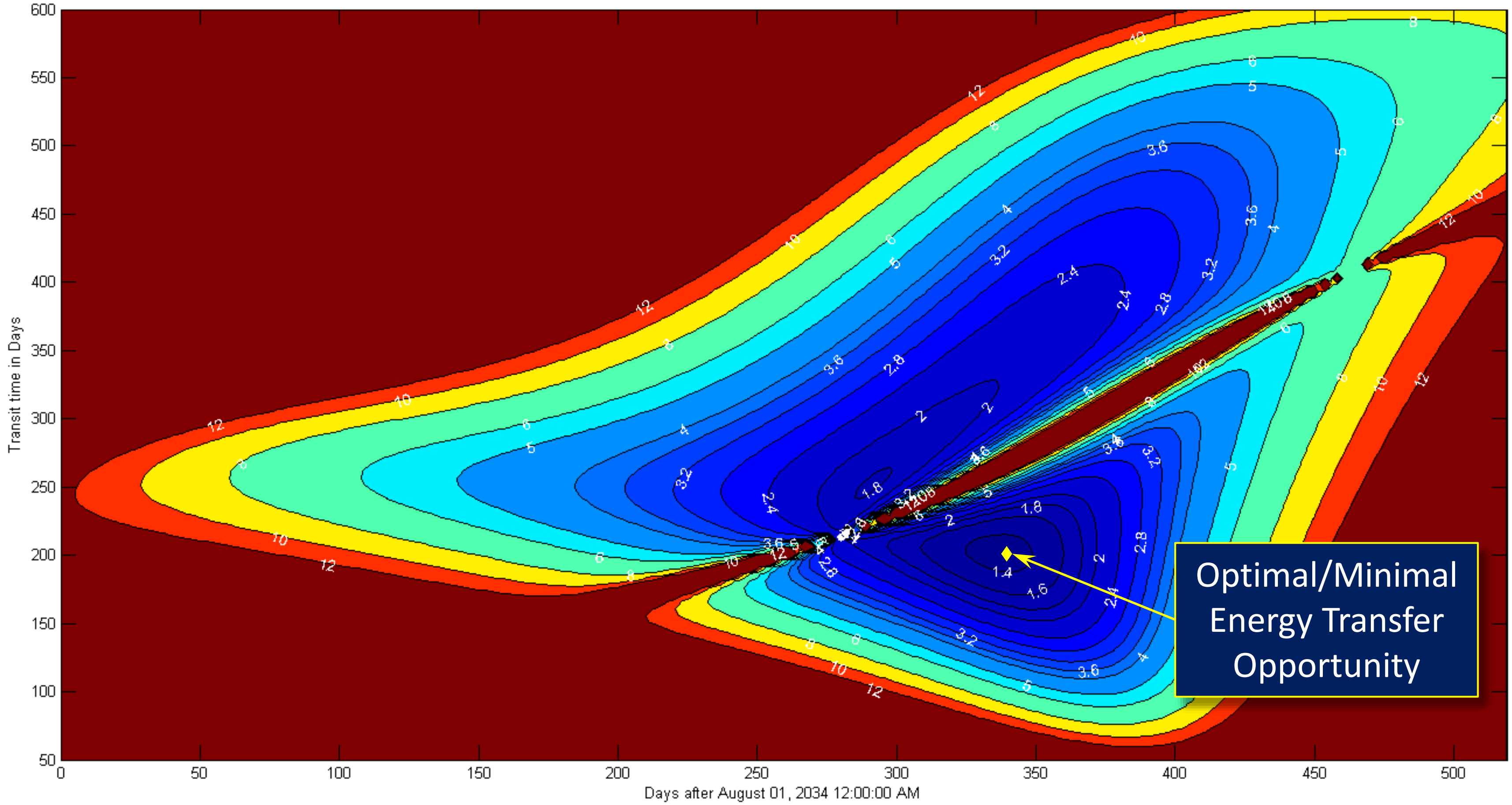


Example Earth-Mars Direct Transit Modes

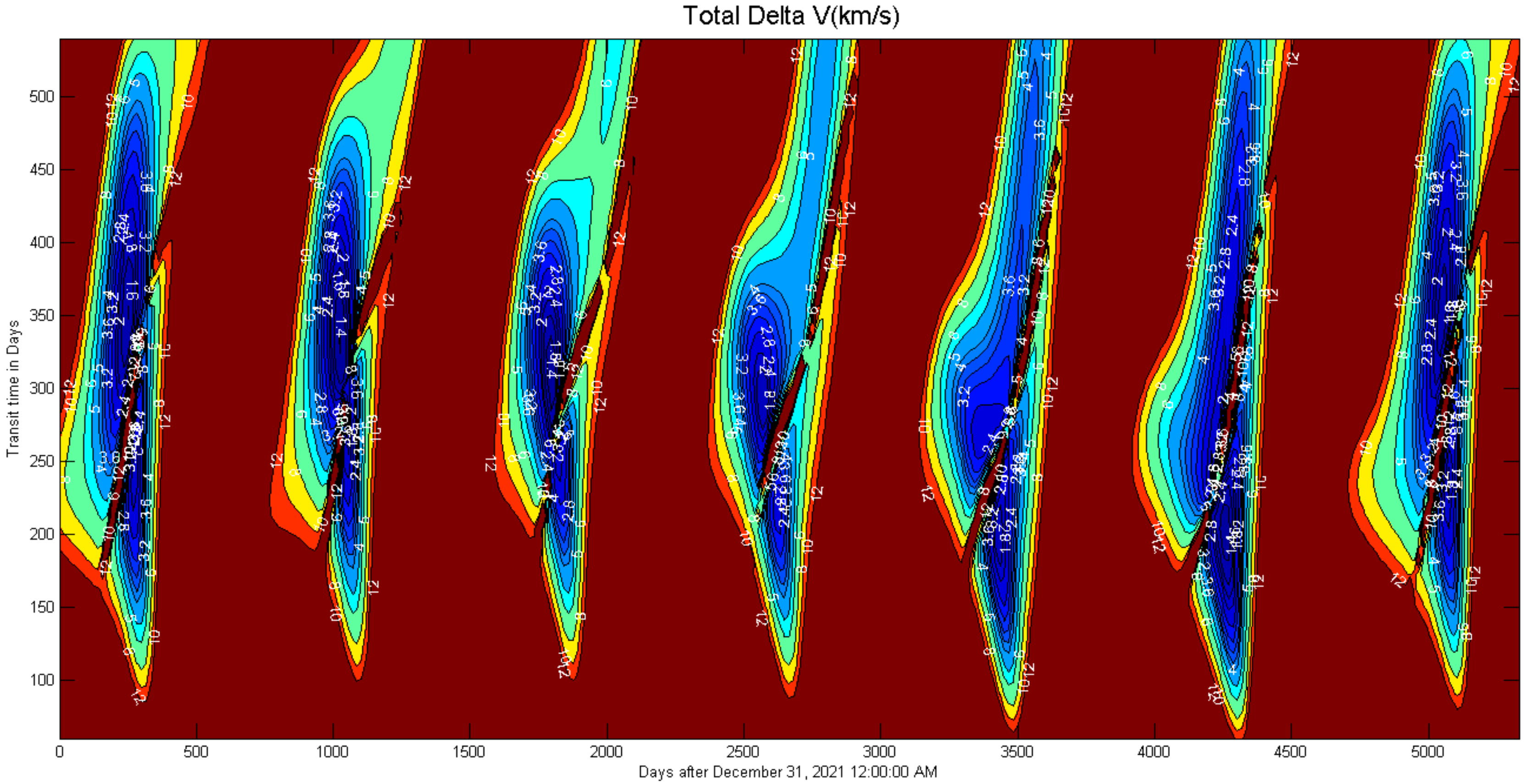
(Earth/Lunar distant aggregation methods also under review, not covered in this initial investigation)



Typical plot of total ΔV (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)

TRANSIT SPACECRAFT - CHEMICAL	value	units
Fuel	MMH	
Oxidizer	NTO	
I_{sp}	315	s
Mass ratio	0.1085	
Propellant mass fraction	0.8915	
Engine mass fraction	0.0060	
Fuel tank mass fraction	0.0221	
Oxidizer tank mass fraction	0.0222	
Structural mass fraction	0.0045	
Dry mass fraction	0.0548	
Payload mass fraction	0.0537	

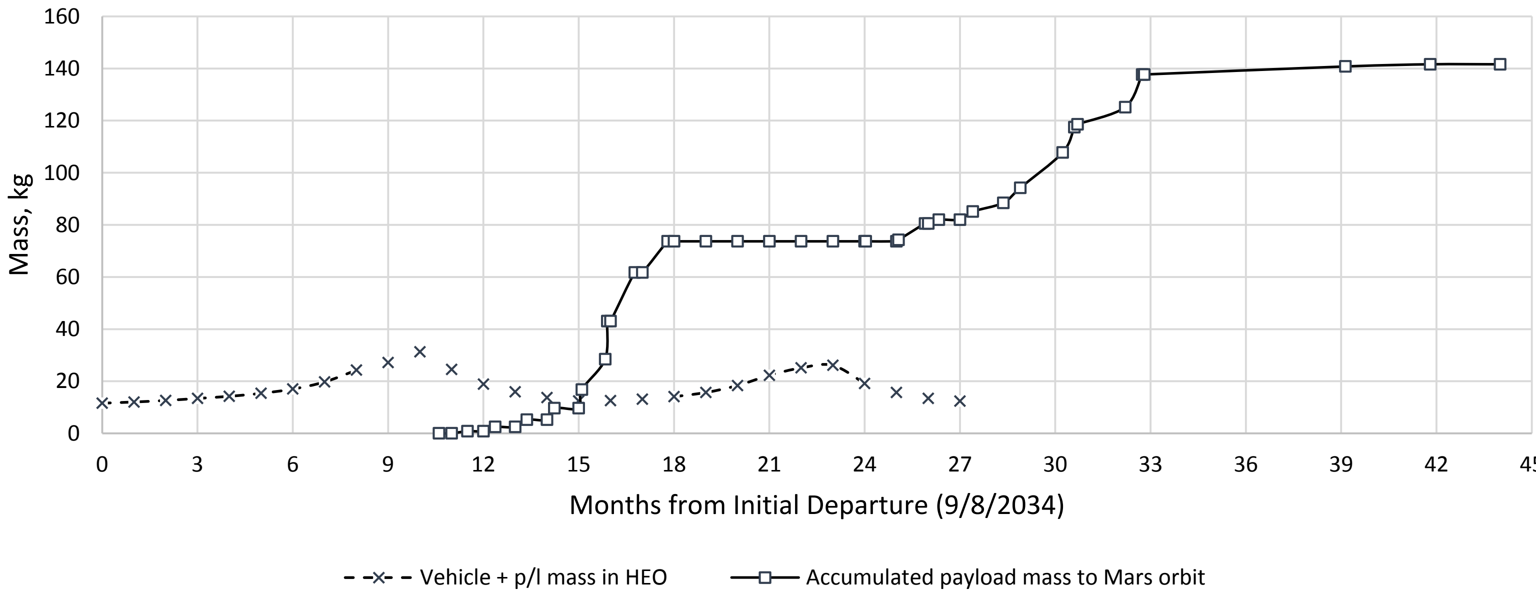
DRY MASS TABLE	value	units
Fuel Tank characterisitics		
Density	875	kg/m3
Safety factor	4	
Material specific density ()	4	kg/m3/Mpa
MEOP pressure	1.8	Mpa
Propellant fraction %	37.74	pct (%)
Oxidizer Tank characterisitics		
Density	1443	kg/m3
Safety factor	4	
Material specific density	4	kg/m3/Mpa
MEOP pressure	1.8	Mpa
Propellant fraction %	62.26	pct (%)
Structural coefficient, εs	0.04	

DRY MASS TABLE (EP)	value	units
Propellant Tank characterisitics		
Density	3080	kg/m3
Safety factor	4	
Material specific density ()	4	kg/m3/Mpa
MEOP pressure	23.44	Mpa
Propellant fraction %	27.5	%
Structural coefficient, εs	0.04	

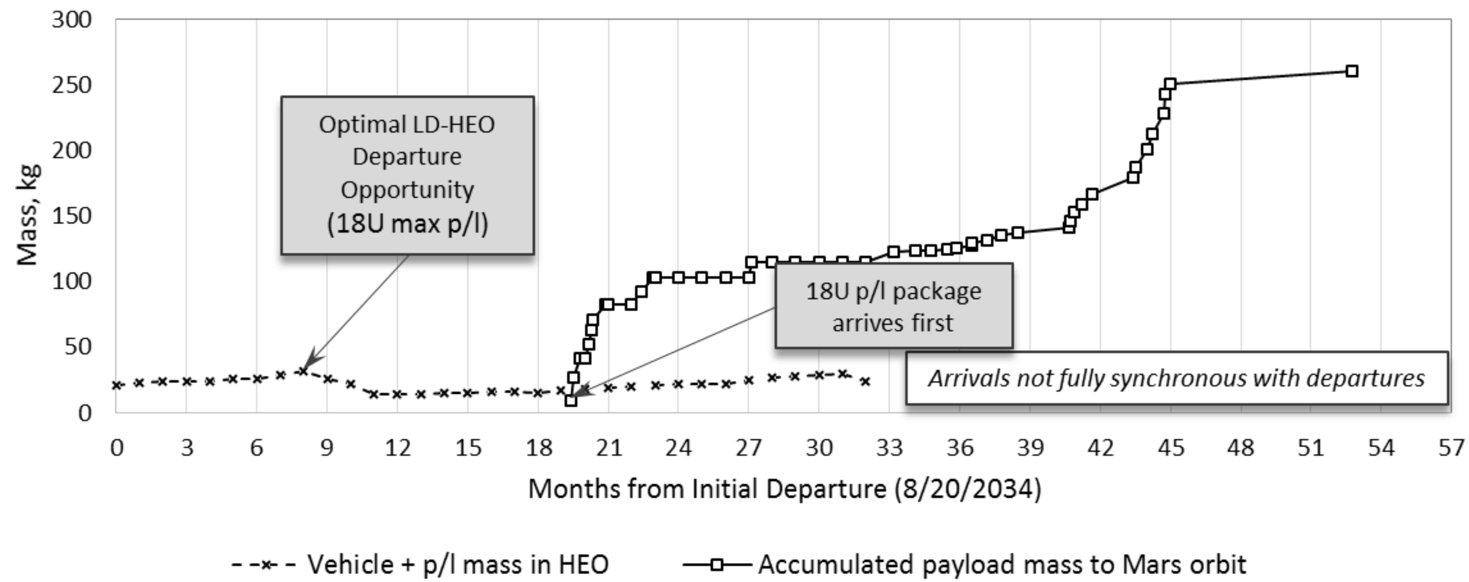
TRANSIT SPACECRAFT - ELECTRIC	value	units
Propellant	Xe	
I_{sp}	3,000	s
Propellant mass fraction	0.2749	
Propulsion Power/Mass	2.7000	W/kg
Thruster efficiency	0.6000	
PPU and Power Efficiency	0.9500	
Propulsion alpha	0.0300	kg/W
Solar power alpha	0.0100	kg/W
Duty cycle (correction)	0.9000	
Structural mass fraction	0.0344	
Dry mass fraction	0.2890	

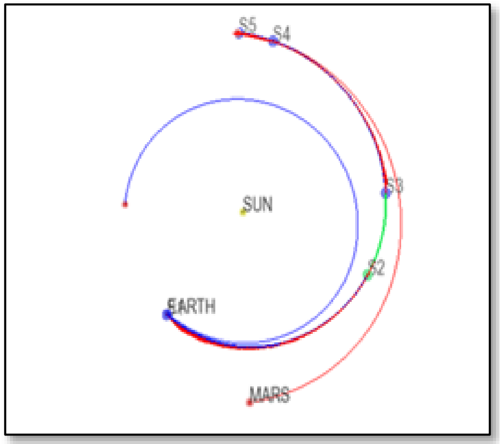
- Spacecraft sizing approach used simple characteristics/mass fraction
- LEO to LD-HEO scale factor of 30% found across launch vehicle classes
- Key Isp parameters were 315 s (chemical); 3,000 s (electric)

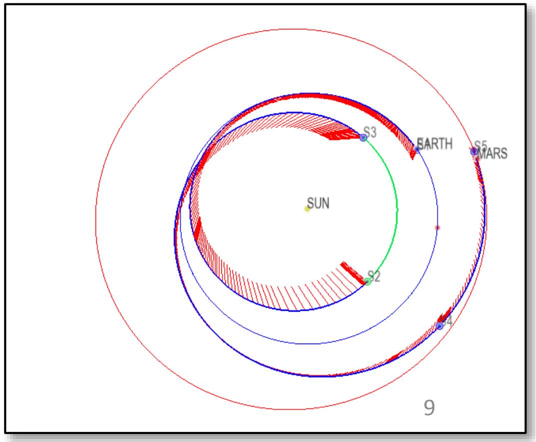
Example plot of chemical system departure and arrival masses across two synodic cycles
(nano-micro launch class delivery case)



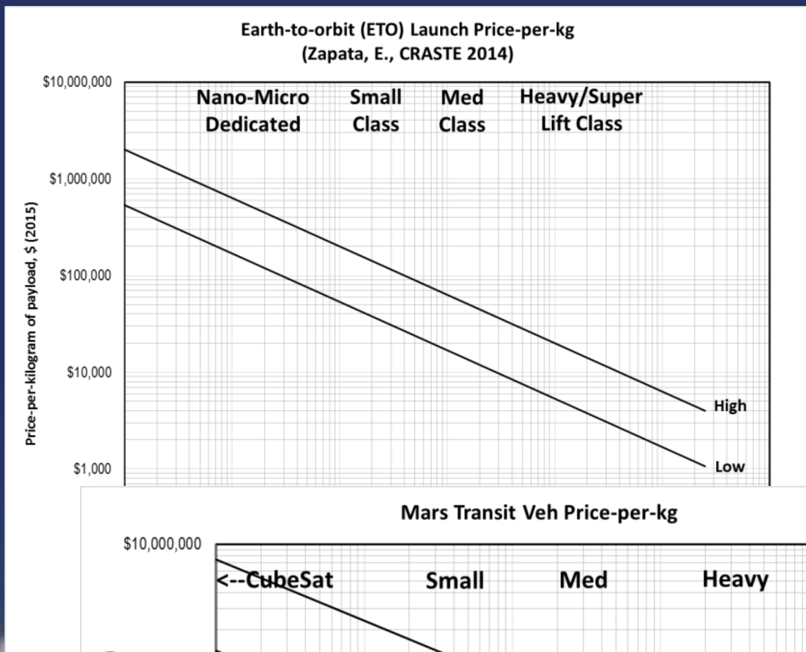
Constant thrust orbital transfer for electric propulsion case in optimal (left) and minimal payload (right) transfers

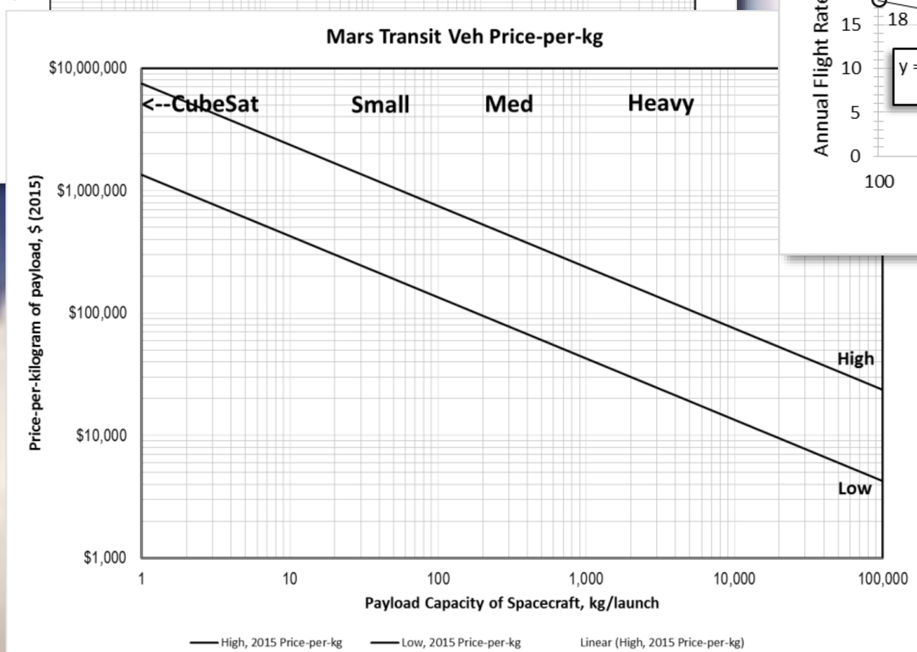


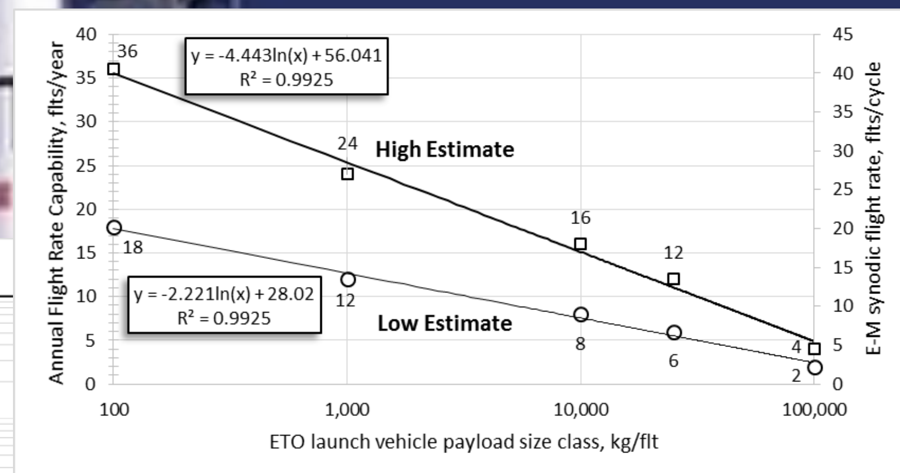




Affordability and flight rate capability parametric plots under investigation







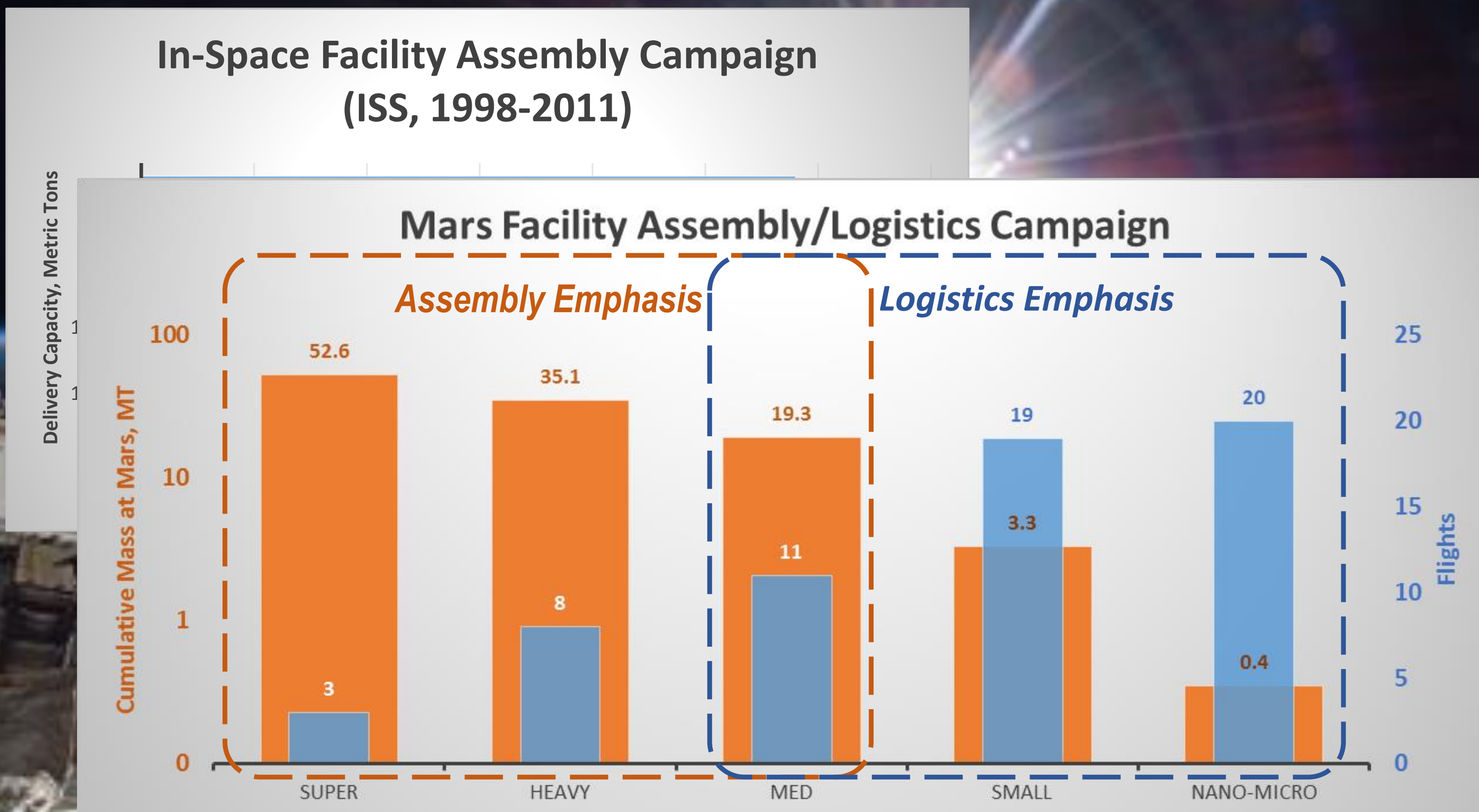
Early results for high-frequency, variable capacity Mars transits from LD-HEO

CHEMICAL PROPULSION MARS TRANSITS	Nano-MicroLauncher	Small Launcher	Medium Launcher	Heavy Launcher	Super Heavy Launcher
ETO Launch Vehicle Capacity to LEO 28.5°(kg/flt)	**100**	**1,000**	**10,000**	**25,000**	**100,000**
Assumed Avg Flt Rate Capacity per veh type (Flts/syn cycle)	26	19	11	8	3
Spacecraft + Payload (kg/flt to LD-HEO w/ 0.313 fraction)	31	313	3,130	7,825	31,300
Cumulative Delivery to LD-HEO (kg/syn cycle to LD-HEO)	407	4,069	30,584	51,408	71,190
Estimated LEO CPK High Average($/kg)	*$200,000*	*$63,240*	*$20,000*	*$12,640*	*$6,320*
Estimated LEO CPK Low Average($/kg)	*$53,410*	*$16,889*	*$5,341*	*$3,377*	*$1,688*
ETO High CPF ($/flt)	*$20,000,000*	*$63,200,000*	*$200,000,000*	*$316,000,000*	*$632,000,000*
ETO Low CPF ($/flt)	*$5,340,000*	*$16,880,000*	*$53,410,000*	*$84,420,000*	*$168,800,000*
Sur					
2034/35 s					

	ELECTRIC PROPULSION MARS TRANSITS	Nano-MicroLauncher	Small Launcher	Medium Launcher	Heavy Launcher	Super Heavy Launcher
LD-HEO Flts	**ETO Launch Vehicle Capacity to LEO 28.5°(kg/flt)**	**100**	**1,000**	**10,000**	**25,000**	**100,000**
	Assumed Avg Flt Rate Capacity per veh type (Flts/syn cycle)	26	19	11	8	3
	Spacecraft + Payload (kg/flt to LD-HEO w/ 0.313 fraction)	31	313	3,130	7,825	31,300
	Cumulative Delivery to LD-HEO (kg/syn cycle to LD-HEO)	626	5,947	30,584	51,408	71,190
	Estimated LEO CPK High Average($/kg)	*$200,000*	*$63,240*	*$20,000*	*$12,640*	*$6,320*
	Estimated LEO CPK Low Average($/kg)	*$53,410*	*$16,889*	*$5,341*	*$3,377*	*$1,688*
	ETO High CPF ($/flt)	*$20,000,000*	*$63,200,000*	*$200,000,000*	*$316,000,000*	*$632,000,000*
	ETO Low CPF ($/flt)	*$5,340,000*	*$16,880,000*	*$53,410,000*	*$84,420,000*	*$168,800,000*
	ETO Cost per synodic cycle-High ($/campaign)	*$400,000,000*	*$1,200,800,000*	*$2,200,000,000*	*$2,528,000,000*	*$1,896,000,000*
	ETO Cost per synodic cycle-Low ($/campaign)	*$106,800,000*	*$320,700,000*	*$587,500,000*	*$675,300,000*	*$506,400,000*
	Derived LD HEO CPK-High ($/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*	*$7,100*
Mars Xfer	Available Monthly Mars Transits (opportunities/syn cycle)[1]	20	20	20	20	20
	Launcher-Capable Transit Opportunities (xfers/syn cycle)	26	19	11	8	3
	Transferred at Optimum Alignment (kg/transit)	**18**	**175**	**1,754**	**4,387**	**17,546**
	Mars 10Sol Accumulation Rate (kg/syn cycle)	**350**	**3,325**	**19,294**	**35,093**	**52,638**
	Estimated Transit CPK High Average($/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*	*$234,080,000*	*$370,120,000*	*$740,240,000*
	Cost-per Transit (expendable) Low ($/flt)	*$4,200,000*	*$13,300,000*	*$42,060,000*	*$66,510,000*	*$133,020,000*
	Transit Cost per synodic cycle-High ($/campaign)	*$468,000,000*	*$1,406,300,000*	*$2,574,800,000*	*$2,960,900,000*	*$2,220,700,000*
	Transit Cost per synodic cycle-Low ($/campaign)	*$84,000,000*	*$252,700,000*	*$462,600,000*	*$532,000,000*	*$399,000,000*
1sol Xfr	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	18,619	33,865	50,796
Surface	Mars Landings	-	19	11	8	3
	Mars 1-sol to surface transfer loss	-	1.22	1.22	1.22	1.22
	Surface Facility Build-up Rate w/ 22% landing loss (kg/syn cycle)	-	2,630	15,261	27,758	41,636

[1] *2034/35 synodic cycle opportunities*

Variety of size classes to construct and sustain large space facilities



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