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Simultaneous Optimization of Spacecraft and Trajectory Design for Interplanetary Missions Utilizing Solar Electric Propulsion

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Background Material

- This talk assumes you were here for the previous companion talks in this session and/or read their papers. This work is important input to this talk and there is not enough time to thoroughly review it.

  - **Lock, et al**, "Potential Campaign Architectures and Mission Design Challenges for Near-Term International Mars Sample Return Mission Concepts" discusses the motivation, previous work, and current study efforts surrounding Mars Sample Return. This includes an architectural description of the current missions under study, their major roles, foreseen implementation, and future trades being considered
  - **Woolley, et al**, "Low-Thrust Trajectory Bacon Plots for Mars Mission Design," describes low-thrust analogs to pork chop plots for Mars missions including the MSR campaign architecture studies. These bacon plots underlie the end-to-end mission analysis for all of the architectures in the current MSR studies.
  - **Laipert, et al**, "Hybrid Chemical-Electric Trajectories for a Mars Sample Return Orbiter," defines methods for developing trajectories for Mars sample return orbiters using both solar electric propulsion and high impulse chemical propulsion systems.

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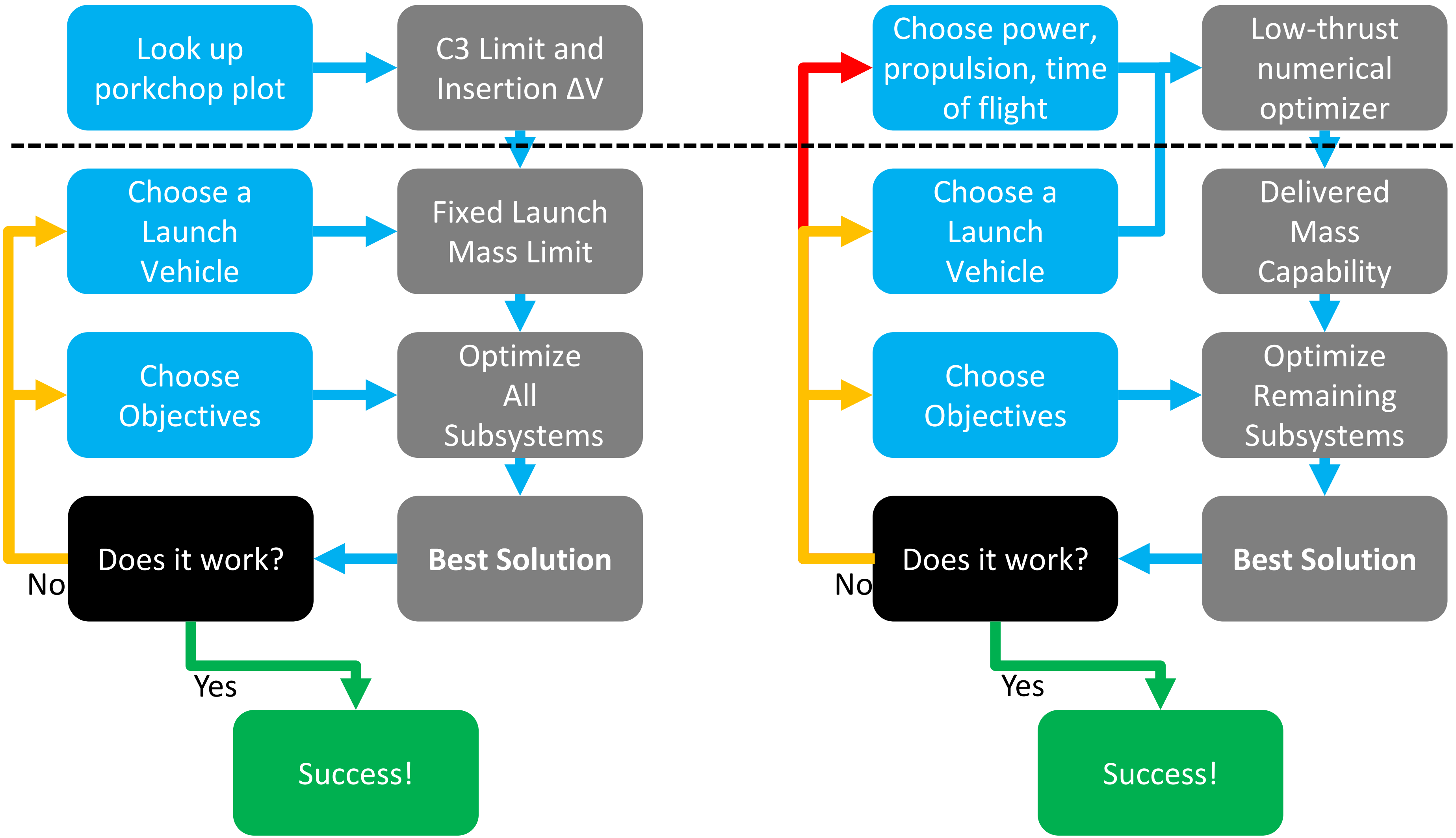
Problem Statement

Ballistic Mission

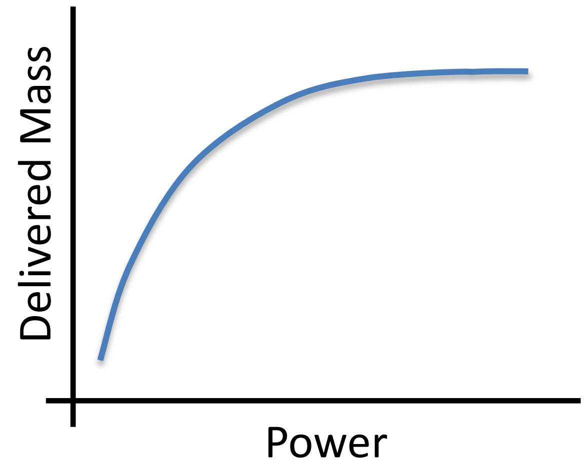
SEP Mission



Which Trajectory To Choose?

(A Simplified Example)

- Delivered mass of EP trajectories tends to have asymptotic performance with respect to power due to thruster saturation



- A mission designer runs a few trajectories in MALTO and gets the following results:

Traj	Power [kW]	Xenon [kg]	Delivered [kg]
1	15	600	1700
2	30	800	2000
3	45	1200	2300
4	60	1400	2400

- Which one is best?
  - Case 4 delivers the most mass
  - Case 3 might be a knee in the curve
  - Case 1 needs the least power

- It depends on the spacecraft!

Which Trajectory To Choose?

(A Simplified Example)

- Let's examine a simplified example where only two parameters are varied and relationships are simple:

A	B	C	D	Spacecraft ID
65	150	90	150	Power Density [W/kg]
12%	12%	6%	6%	Tank Fraction [%]

Rest of Bus [kg]	1000
Thruster Throughput [kg]	250
Thruster Mass [kg]	50
Structures Fraction	10%
Propellant Margin	10%

(same for all designs)

Traj	Power [kW]	Xenon [kg]	Delivered [kg]
1	15	600	1700
2	30	800	2000
3	45	1200	2300
4	60	1400	2400

Useful P/L	A	B	C	D
Traj 1	55	185	160	225
Traj 2	10	275	190	325
Traj 3	-120	275	150	350
Traj 4	-345	175	5	270
Best	1	2 or 3	2	3

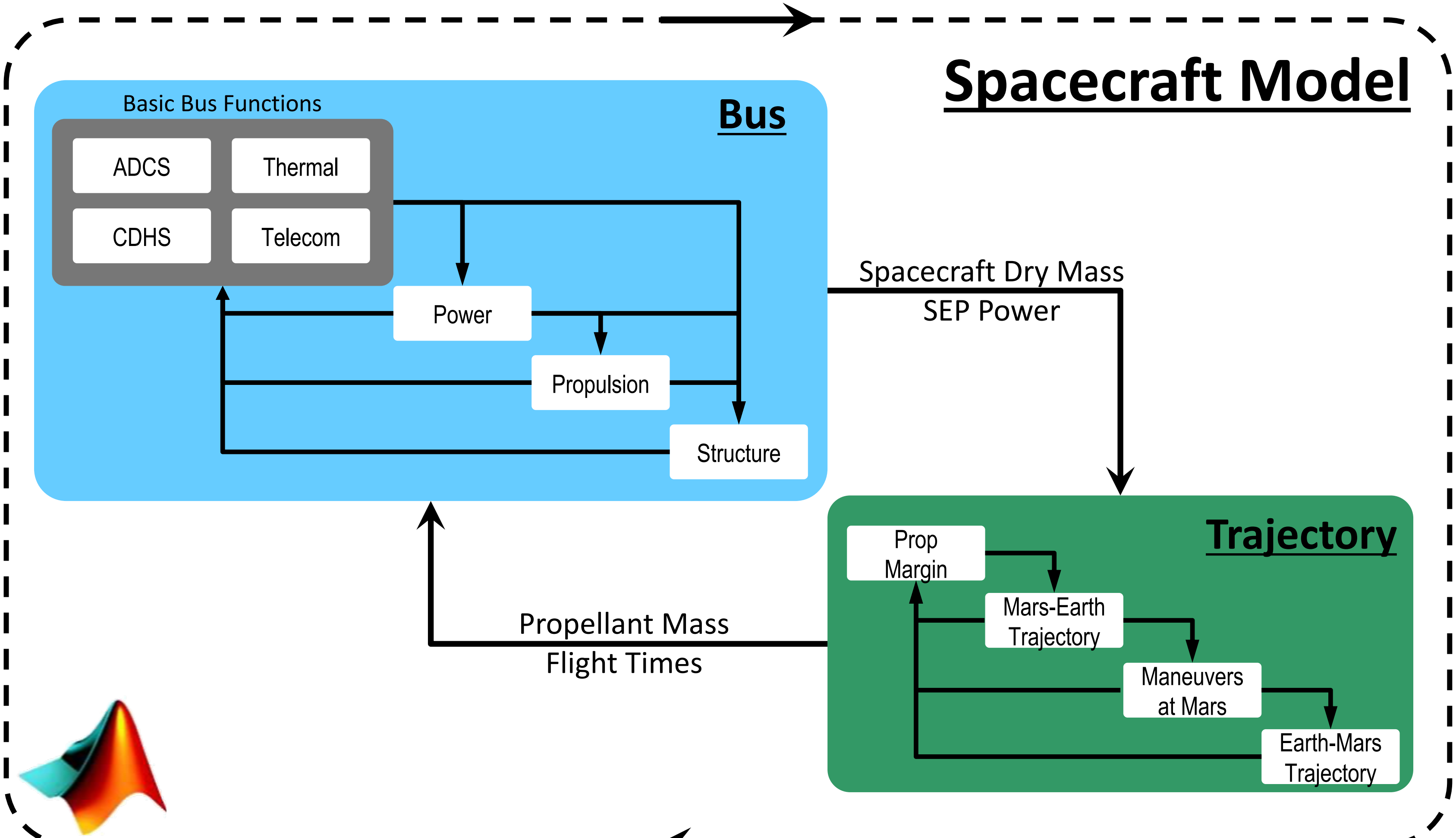
Extra performance of Traj 4 outweighed by system impacts, is not the correct choice for any option

- Conclusions:
  - different spacecraft prefer different trajectories
  - the useful payload varies significantly with spacecraft design parameters (factor of ~7 in this example), so it matters a lot
- Wouldn't it be great if there was a way to optimize this?

Mars ORbiter Tool (MORT)

Simultaneous Spacecraft/Trajectory Optimization

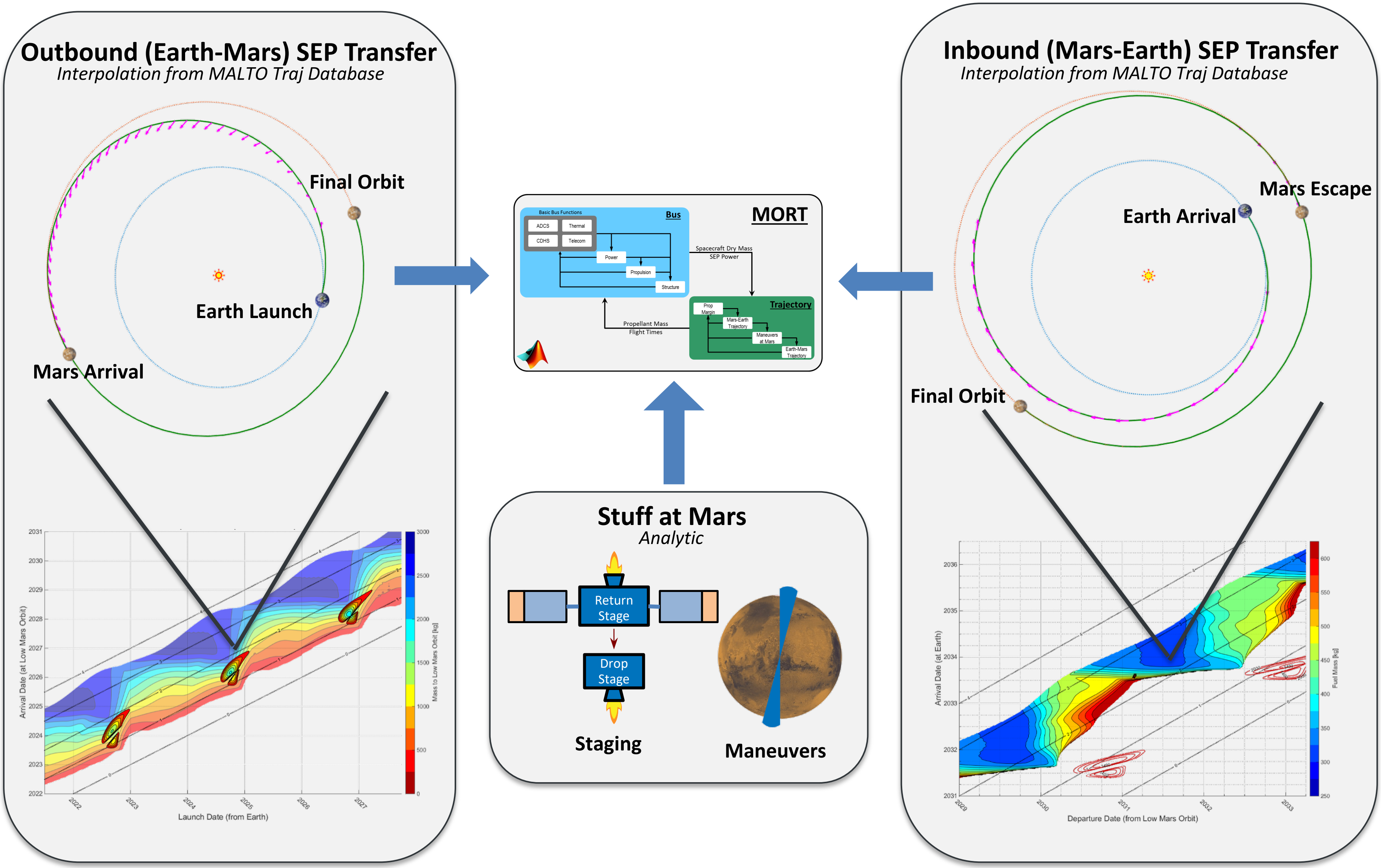
User's Design Inputs
- Year
- LV
- Power
- Thruster
- Margins



Converged Design
Feasible Trajectory
Figures of Merit

A single run takes < 1 sec, so it is suitable for optimization and parameter sweeps

Trajectory Modeling – MSR



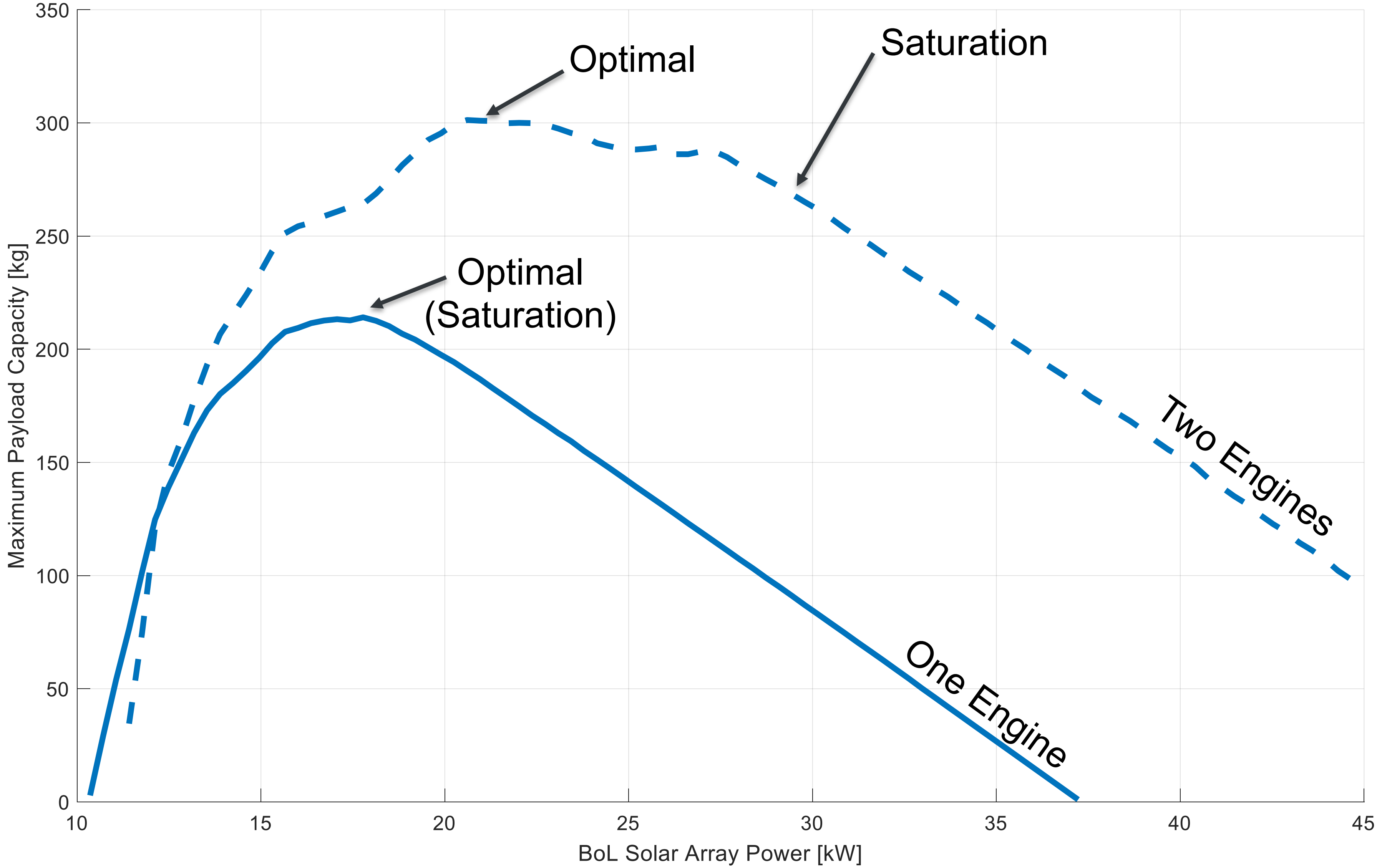
Pre-Decisional Information – For Planning and Discussion Purposes Only

Subsystem Models

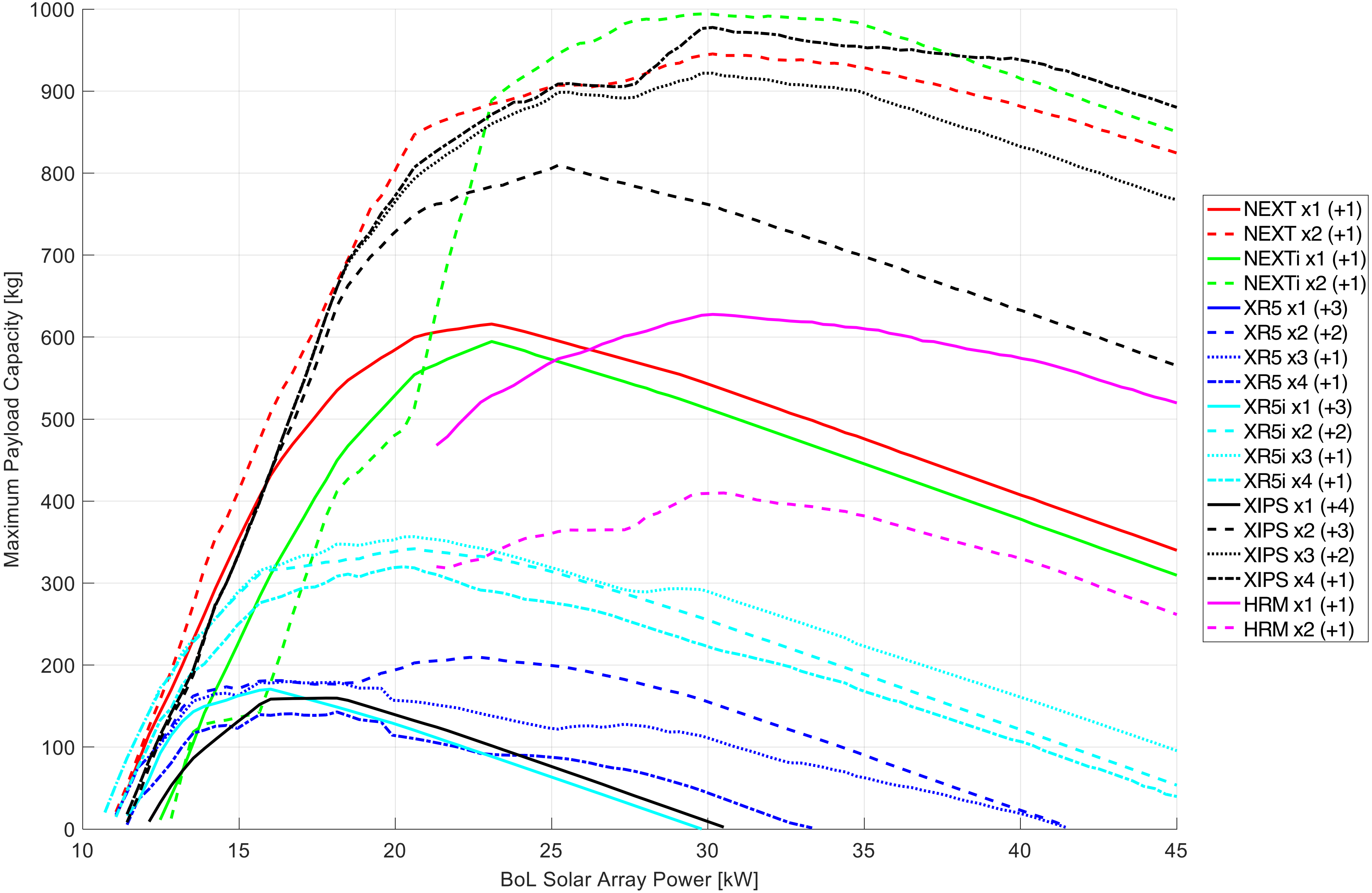
- **Modular** – any block is replaceable
- **Variable Detail** across subsystems
- **Upgradeable** as fidelity improves
- Example: Thermal Subsystem

Generic Rule of Thumb	**Thermal Mass** = x_0% of S/C Dry Mass
↓	
Analogue to Prev Mission	**MLI** = x_1 * Bus Surface Area [m^2] **Heat Pipes** = x_2 * (PPU Waste Heat + Bus Waste Heat) [kW] **Misc (heaters, thermostats, etc)** = x_3 * Characteristic Length [m]
↓	
Expert Low-Fi Modeling	**Refine** x_1, x_2, x_3 and scaling relationships
↓	
Detailed Models	**Incorporate** model directly or input the detailed hardware items

Typical Result

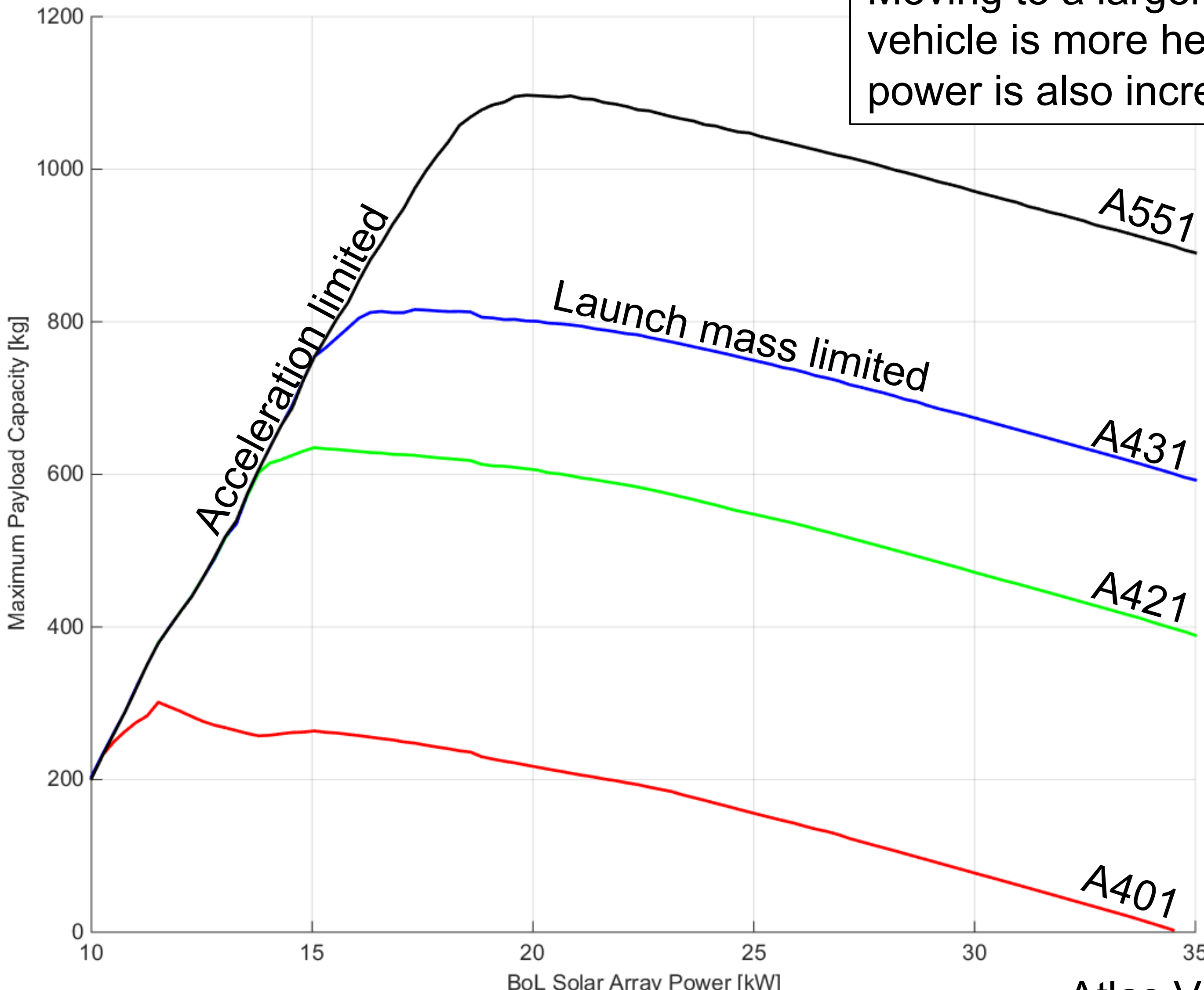


Trends with Propulsion



Trends with Launch Vehicle

Moving to a larger launch vehicle is more helpful if power is also increased!



Atlas V series launch vehicles

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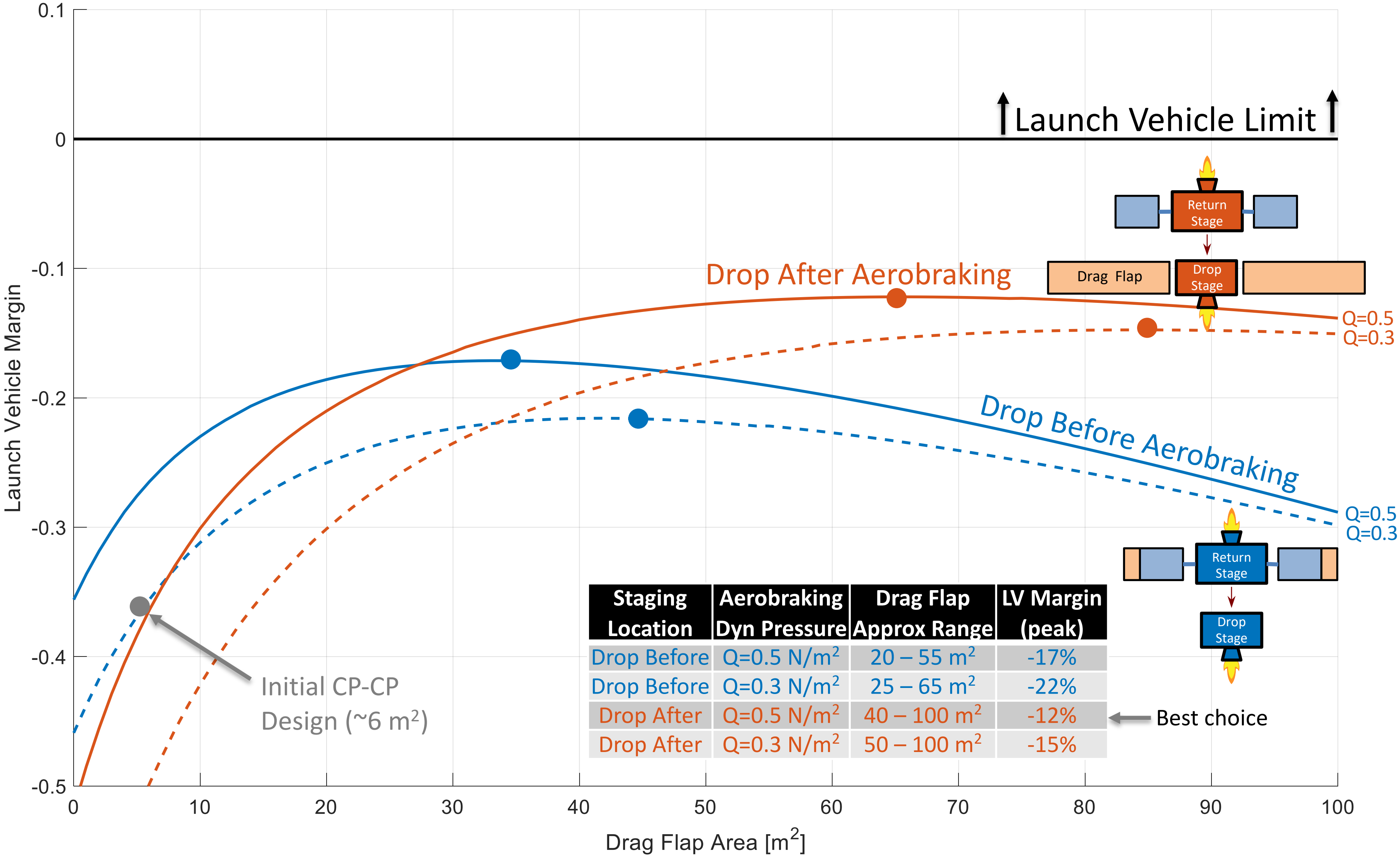
MORT also works for CP!



Staging Location	Aerobraking Dyn Pressure	Drag Flap Approx Range	LV Margin (peak)
Drop Before	Q=0.5 N/m^2	20 – 55 m^2	-17%
Drop Before	Q=0.3 N/m^2	25 – 65 m^2	-22%
Drop After	Q=0.5 N/m^2	40 – 100 m^2	-12%
Drop After	Q=0.3 N/m^2	50 – 100 m^2	-15%

Best choice: Drop After, Q=0.5 N/m^2

Conclusions

- MORT is an extremely powerful tool in the formulation of SEP missions, enabling quantitative trade studies otherwise impractical that are fundamental to improving performance

- This talk cannot capture the full utility of MORT. In the past few years, it has been used for:
  - **Concepts**: Remote Science, Telecom, Daughtercraft/Multifunction, Sample Return, Crew/Crew Cargo
  - **Size Class**: SmallSat (up to 100kg), Robotic (up to 10,000 of kg), Crewed (up to 100,000 kg)
  - **Mission Modes**: Direct Launch, Rideshare, Refueling/Refurbish