Breaking the Rocket Equation: How Refuellable Satellites Change In-Orbit Transportation

SSC22-P1-09

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Abstract

One of the chief tenets of space transportation has been the immutability of the Tsiolkovsky rocket equation, placing great emphasis on the specific impulse of a thruster to determine the propellant mass. For applications where all propellant must be carried from the start, this drives most vehicle designs to the highest possible ISP. The compromise is the typical tradeoff between ISP and thrust magnitude. Thus, transfers which require either impulsive maneuvers or a tight timeline will favor low-ISP platforms.

If adequate infrastructure is provided to allow for a refuellable spacecraft, a smaller and lighter vehicle can be used. This vehicle will have a payload mass fraction more in line with an equivalent system with many multiples higher specific impulse. As effective specific impulse increases to values approaching the highest performance electric propulsion systems, the time to destination remains of the same order of magnitude as an impulsive orbital maneuver.

Further work must be done to optimize for the positioning and design of fuel depot infrastructure, especially bearing in mind both interactions with high radiation in the Van Allen belts, and ideal orbital planes to seed with these refuel depots.

Background

- All reaction mass propelled vehicles inherently limited by Tsiolkovsky Rocket Equation
- $\Delta V = I_{sp} g_o \ln {}^{m_o}/_{m_f}$
- Launch vehicles get around this by staging
- More difficult with satellites, typically thrust and ISP are only levers, trading payload mass with travel time.

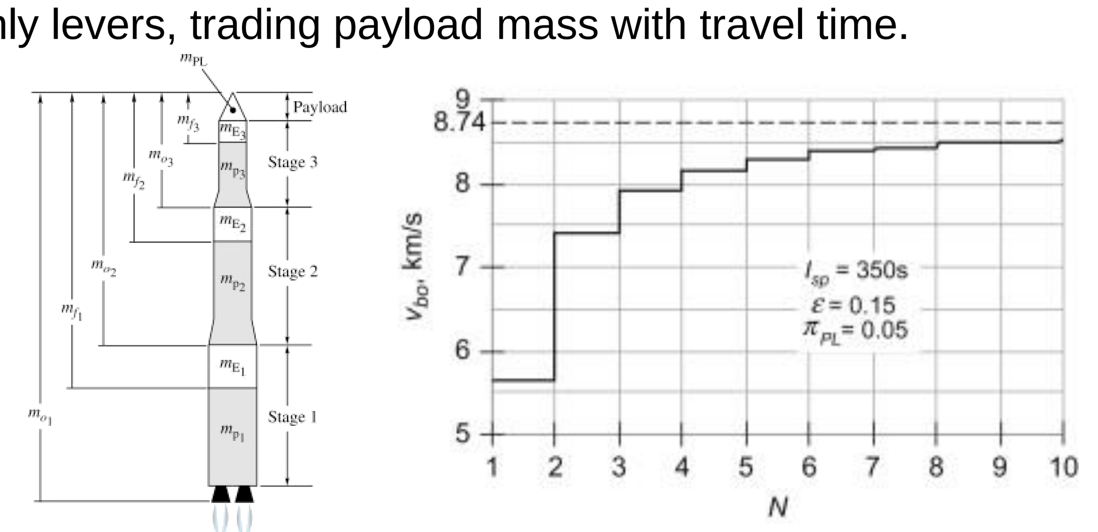

Figure 1: Example launch vehicle & burnout velocity vs. number of stages (Curtis 2010, Figs 11.7, 11.8)

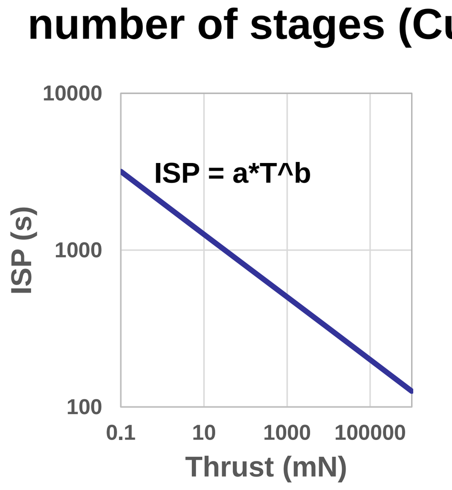

Figure 2: Example tradeoff between thrust and ISP

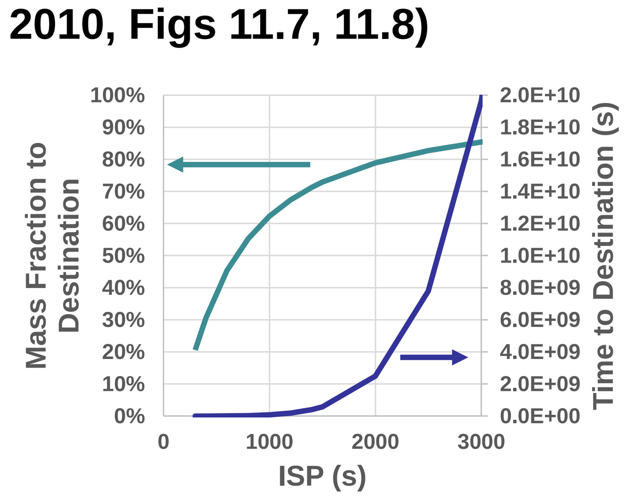

Figure 3: Effect of ISP on mass fraction and travel time: 300km circular to GEO Edelbaum transfer

Orbital Transfer Methods

- Compare in-plane circular-to-circular orbit transfers
- Typical choices are a low-thrust spiral Edelbaum orbit to make use of high ISP thruster, or a high-thrust Hohmann transfer to make use of a more efficient and faster impulsive transfer

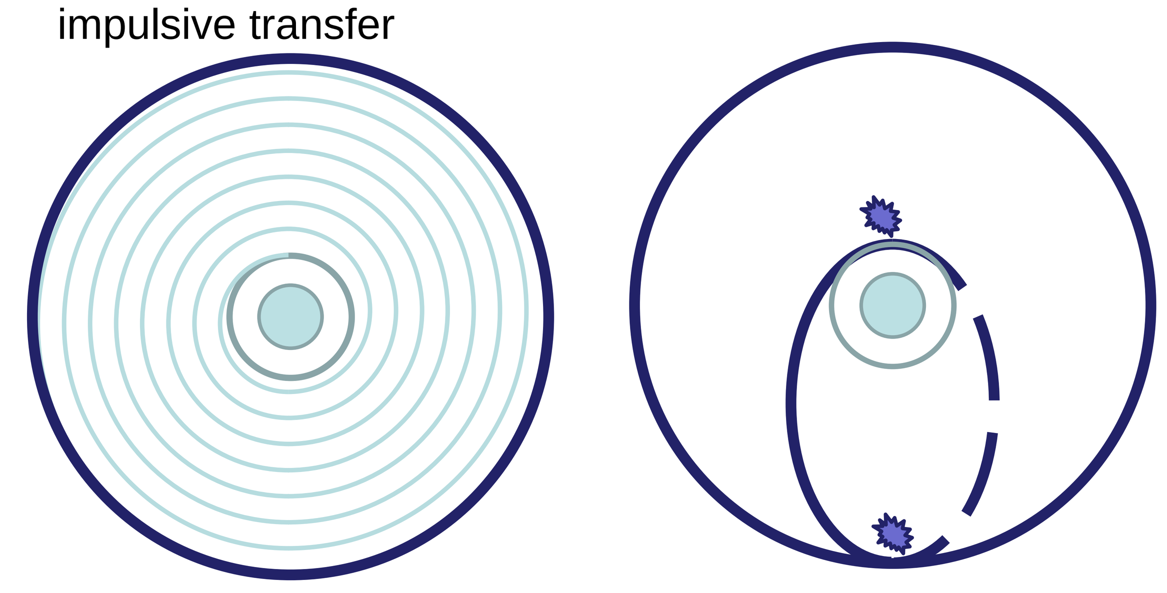

Figure 4: Examples of Edelbaum and Hohmann transfer orbits.

Lessons from Aviation

- In-Air refueling exists to allow inefficient, high-thrust aircraft to extend range or reach its destination faster
- Similar practice could be employed for satellites, if sensible locations for refuel depots can be ascertained

Figure 5: Example of in-air refueling (Graham 2013)

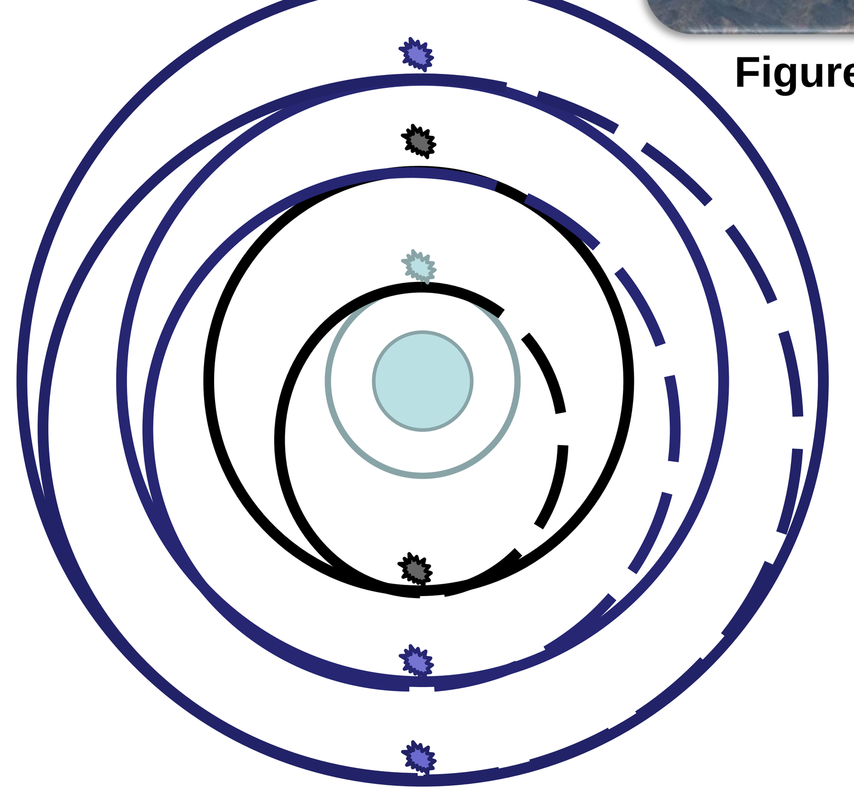

Figure 6: Example Multi-Hohmann Transfer with Refuel to same final orbit as Figure 4.

Design Reference Mission

- Evaluate multiple Hohmann transfers to get to destination altitude. Assume consume same propellant for each leg
- Baseline a 300s ISP, 600kg starting mass, 300km starting altitude
- Assume complete a 2-burn Hohmann transfer between two circular orbits before refuel. Refuel is instantaneous

Effect on Mass, ISP

- Ability to refuel increases mass fraction to destination
- Increased mass fraction consistent with higher ISP
- $ISP_{effective} = ISP_{thruster} * N_{legs}$
- 300s thruster refueled 4 times equivalent to 1500s.

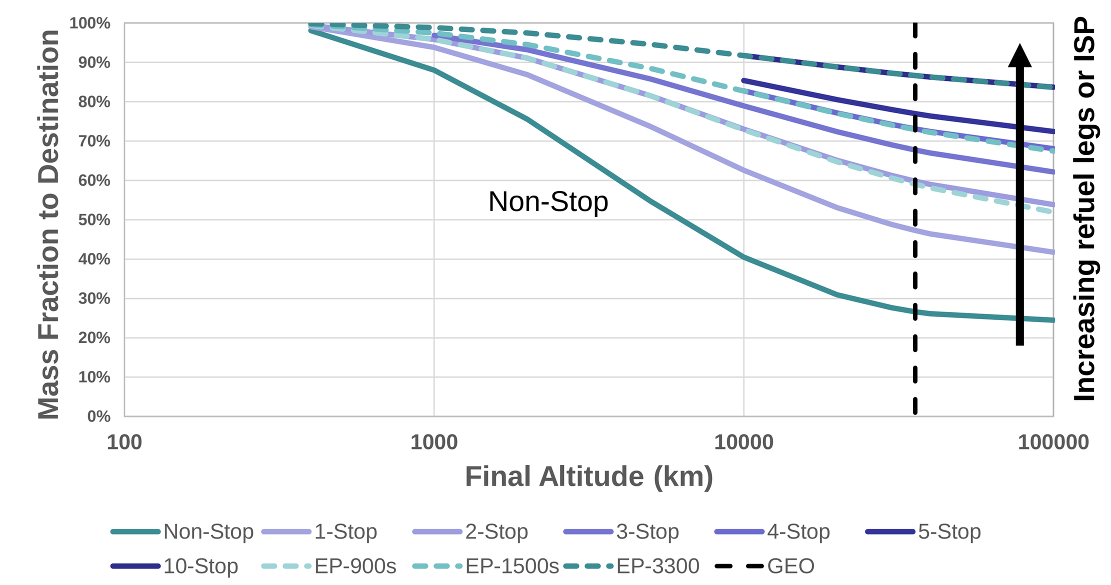

Figure 7: Effect of refuel on mass fraction to destination, comparison to high ISP spiral orbits. GEO altitude for reference.

Effect on Transit Time

- Multiple refuel stops necessarily increases transit time
- For low altitudes, transit time scales with numbers of refuel stops as all stages have roughly same transit time as single Hohmann transfer
- For high altitudes, transit time still increases but at better than 1:1 scaling, due to greater number of transfer stages spent at low altitude, shorter period orbits
- Not accounted for is any additional time to match orbit and dock with refuel depot or transfer propellant
- Almost all increases in transit time are still faster than an Edelbaum transfer to the same altitude. In this case compared to a hypothetical 300s, 13N thruster
- Note that lower thrust, higher ISP transfers have many orders of magnitude slower transit times and are not shown on graph

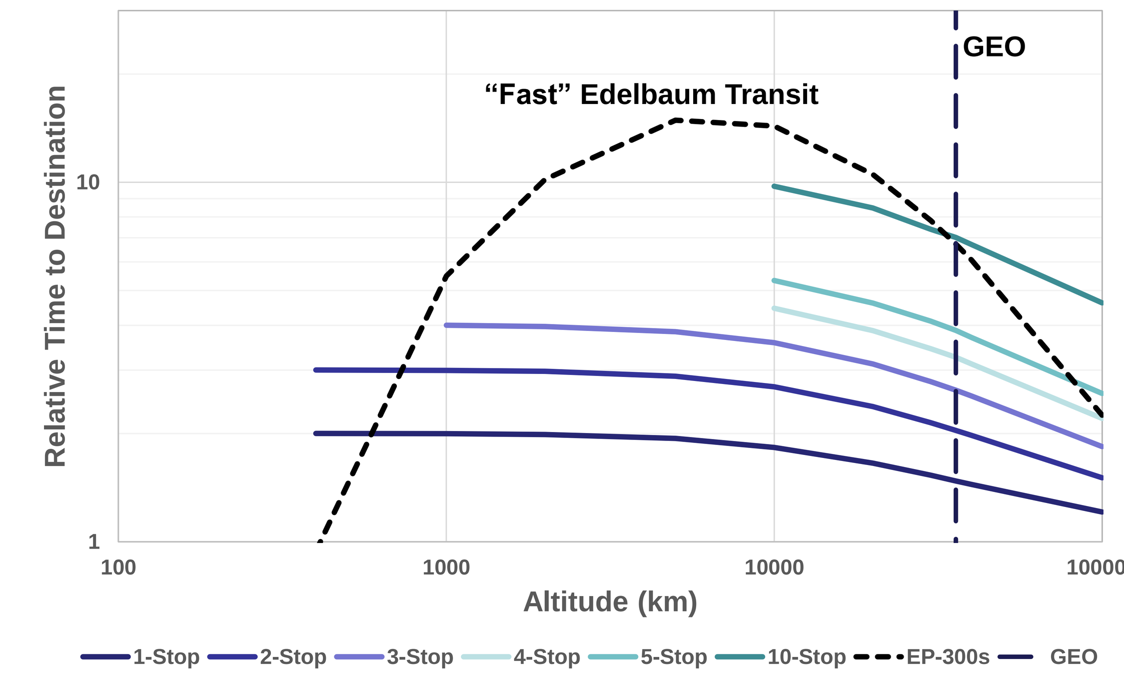

Figure 8: Transit time relative to a non-stop Hohmann Transfer. GEO altitude shown for clarity.

Challenges

- This simplified model does not account for needs of customers to change inclination, RAAN, etc.
- If servicing multiple propulsion systems, must stock and maintain depots of multiple material streams
- Loiter altitudes are in or near the Van Allen belts, may impose radiation constraints on customers or depots

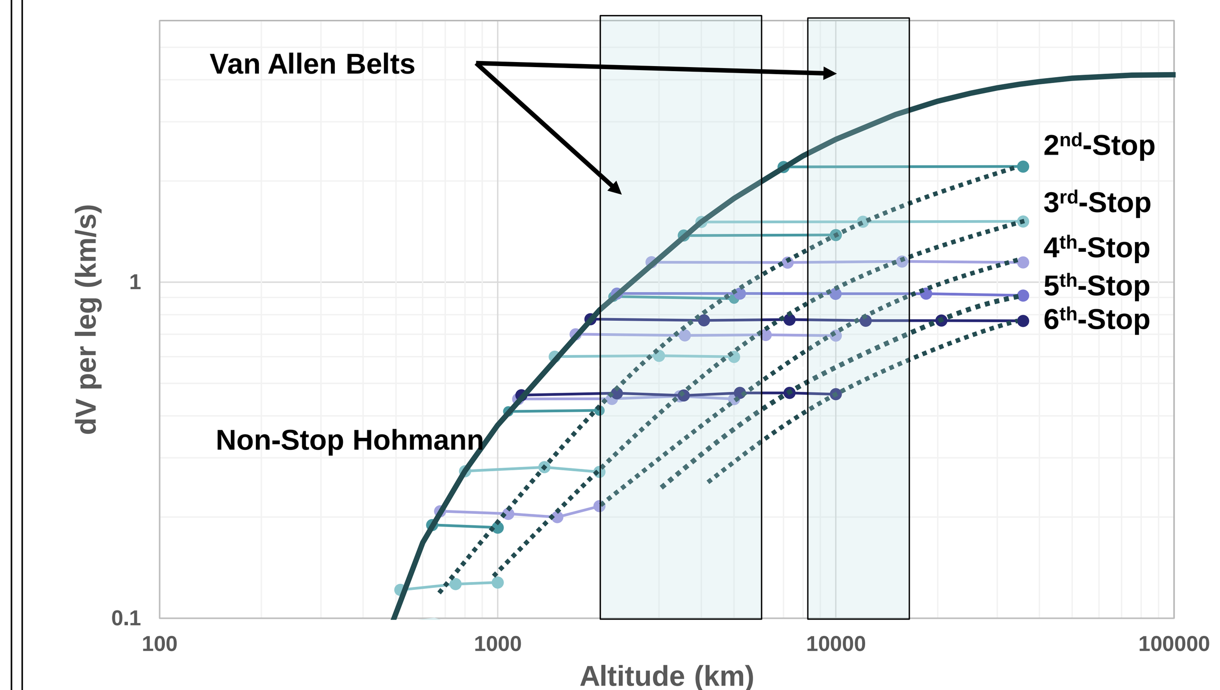

Figure 9: dV per leg versus final altitude of each leg. Curves of 0th, 1st, 2nd etc. stop overlaid

Conclusions

- Refuellable spacecraft and orbital transfer vehicles offer the ability to carry EP equivalent payload fractions to destination orbits in only a fraction of the time
- The effect on "virtual" ISP is a simple multiple of the base ISP and the number of transit legs
- The effect on transit time is, to a first order, a simple multiple of the non-stop Hohmann transit time and the number of transit legs. At higher altitude destinations the transit time is further reduced
- While more work needs to be done, altitudes to refuel based on start point and destination are readily predicted
- Challenges remain due to number of fuel stops required within the Van Allen belts. Customers may actually have lower total radiation dose than an EP transfer due to reduced transit times. For fuel depots, this poses a significant design challenge favoring passive systems.
- Further tailoring of flight plans is possible at expense of longer transit times or carrying more propellant
- Future work to investigate interaction of changes to orbital plane

References

- Curtis, Howard D. "Orbital Mechanics for Engineering Students (Second Edition)" 2010
- Gaylor, David E. "Low Thrust Circle-To-Circle Orbit Transfer" 2002
- Col. Graham, Richard H. "SR-71: The Complete Illustrated History of the Blackbird, The World's Highest, Fastest Plane" 2013

Acknowledgements

- Rob Schwarz
- Nathan Orr
- Max Brand