National Aeronautics and
Space Administration

white paper

2023 Moon to
Mars Architecture

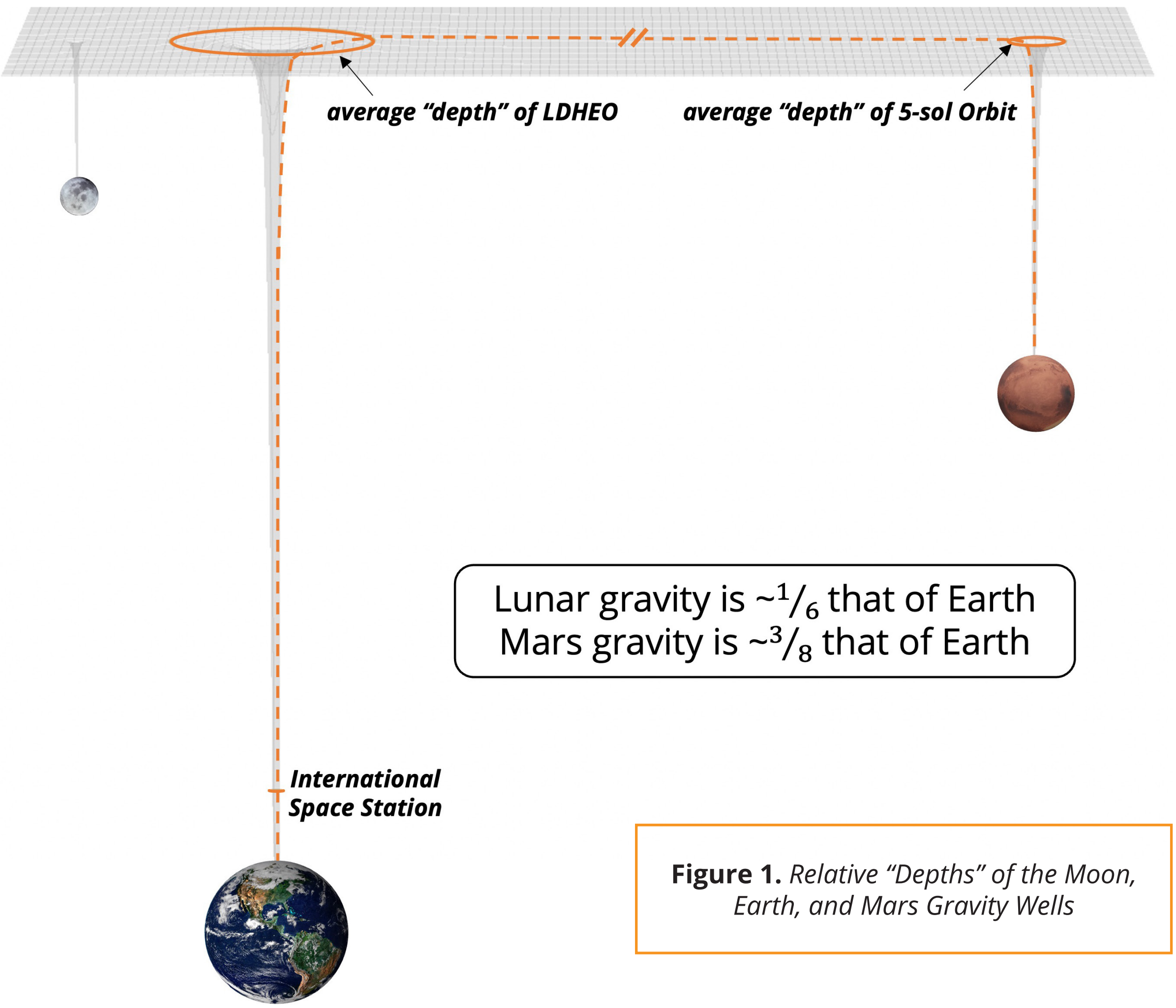
Round-Trip Mars Mission Mass Challenges

Introduction

As noted in the 2022 Architecture Concept Review “Mars Transportation” white paper, the distance between Earth and Mars changes constantly as the two planets revolve around the Sun. Regardless of their relative positions, traveling to Mars requires significantly more energy than lunar missions. However, the distance between the planets is only part of the story. This white paper explains how gravity wells, combined with the distance and desired transit duration between them, serve as a mass, and potentially cost, multiplier for a round-trip human Mars mission.

Escaping from a Gravity Well

A gravity well is one way to visualize the gravitational pull exerted by a large body in space. The “depth,” or strength, of a given gravity well is a function of the planetary body’s mass, with the bottom of the well terminating on the body’s surface. For example, Mars is smaller and less massive than Earth, so Mars’ gravity well is shallower than Earth’s gravity well; the Moon is even less massive than Mars, so the Moon’s gravity well is much shallower than either Earth’s or Mars’ gravity wells, as depicted in Figure 1.



Lunar gravity is ~$^{1}/_{6}$ that of Earth
Mars gravity is ~$^{3}/_{8}$ that of Earth

Figure 1. *Relative “Depths” of the Moon, Earth, and Mars Gravity Wells*

Gravity wells help visualize part of the mass challenge that a round-trip human Mars mission poses. Most people can appreciate that climbing up a taller hill (or climbing out of a very deep well) requires more physical exertion than climbing up a smaller hill (or climbing out of a very shallow well). Consider the exertion required to "climb" from a planetary body's surface to orbit, but with exertion measured in kilograms (kg) of rocket engines and propellant instead of calories burned.

For example, visualizing the depth of Earth's gravity well versus the Moon's helps explain why Apollo astronauts required the large Saturn V rocket just to escape Earth's gravity well and reach the Moon, but could escape from the Moon's gravity well and return to Earth with a much, much smaller vehicle.

Ascent from the surface of a gravitational body not only requires the thrust necessary to counteract gravity and ascend to a target altitude, but also that the spacecraft match the orbital velocity of the target orbit. Proximity to a gravitational body determines the gravitational pull that body exerts on the spacecraft.

For circular orbits, which have a near-constant orbital altitude, the gravitational pull will be constant. For elliptical orbits, the gravitational pull will vary over the course of the orbit as the distance between the spacecraft and gravitational body changes. Highly elliptical orbits, which are extremely elongated (e.g., lunar-distance high-Earth orbit (LDHEO) or the 5-sol Mars orbit) spend a significant percentage of their orbital period at distances far from the gravitational body, meaning that the "average" depth of these orbits is near the top of the gravity well. Orbits near the top of the gravity well generally require less effort to escape than orbits closer to the bottom of the well.

However, depth in a gravity well is not the only factor to consider when evaluating the relative difficulty of escaping a gravitational body. Escaping requires a spacecraft to achieve enough kinetic energy — the energy due to its orbital velocity — to overcome the gravitational pull. Like the gravitational pull, orbital velocity increases and decreases over the course of a period in an elliptical orbit. Although gravitational pull is reduced at farther distances, departure burns from elliptical orbits are typically done near closest approach, where the difference between the kinetic energy of the spacecraft and the kinetic energy required to escape is at a minimum.

Interplanetary Transit and Capture

Reaching Mars requires not only the energy to climb out of Earth's gravity but additional energy to transit the distance between Earth and Mars. While Figure 1 is useful for visualizing the relative "depths" of gravity wells, it does not capture the changing distance between gravity wells.

Both Earth and Mars orbit the Sun, but travel at different velocities, so the distance between them is constantly changing. Over the course of their 780-day synodic period, this separation varies by between 56 and 400 million kilometers, but a spacecraft cannot simply travel in a straight line between them. Instead, a spacecraft must traverse in parabolic paths (Figure 2) shaped by the Sun's gravity and the desired transit time between Earth and Mars. The transit time between the planets determines the distance traveled and the amount of energy that must be expended to accomplish the mission. Fast transits between Earth's and Mars' gravity wells can be more expensive (in terms of energy) than escaping their respective gravity wells.

In addition to distance, the relative velocity of the planets, mission duration, and orbital stay time all influence the interplanetary energy required to reach Mars. A vehicle departing Earth must expend energy to accelerate toward Mars — and then expend more energy to match Mars' speed once it arrives at Mars vicinity. A vehicle must slow down as it gets closer to a planet before it can "fall" into the planet's gravity well. If the vehicle is going too fast, it can easily "skip" over the gravity well, much like a fast-moving golf ball skipping over a golf hole.

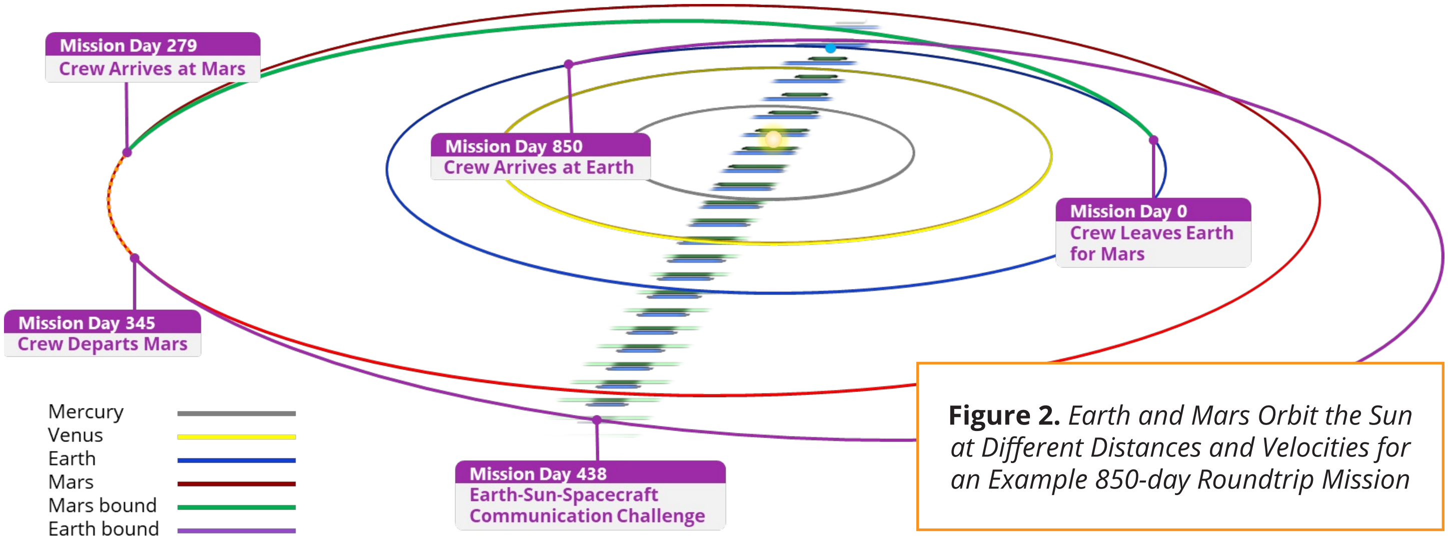


Figure 2. *Earth and Mars Orbit the Sun at Different Distances and Velocities for an Example 850-day Roundtrip Mission*

How fast a spacecraft travels is a function of the desired transit time between planets; faster requires more transit energy but reduces trip time. For the sake of minimizing crew exposure to the space environment, faster is better (for the crew), but faster comes with an enormous energy penalty that results in increased propulsion system and propellant mass.

Minimum-energy missions utilize optimal planetary alignment for each leg of the interplanetary transit, resulting in a long (300 days or longer) loiter period at Mars and a round-trip mission duration of about 3 years. Trip time can be reduced by optimizing planetary alignment for only one leg of the mission, paired with a short loiter period at Mars, for a round-trip duration on the order of about 2 years, but at the expense of additional interplanetary energy expended on the non-optimal leg.

Shortening transit times between bodies generally increases the propulsive energy the transit vehicle must deliver. Short transits require acceleration to a higher energy state and consequently approach their target with higher excess velocity. Longer transits provide more time to obtain minimum energy transfers through optimal planetary alignment. The 2022 Architecture Concept Review "Mars Transportation" white paper used an 850-day round-trip mission (Figure 2) to compare several transportation options.

The energy required to capture into a body's gravity well is generally applied quickly at the point of closest approach to reduce the relative velocity of the capturing spacecraft. Although the body continues to exert its gravitational force on the spacecraft while in orbit, pulling it toward the surface, the translational velocity of the spacecraft keeps it in orbit. A de-orbit burn to arrest this translational velocity and slow down further allows the body's gravitational force to pull the spacecraft down to the surface. Typically, crewed and uncrewed landing systems remove orbital energy following the de-orbit burn to maintain a safe landing velocity.

One Way v. Round-Trip Missions

All robotic Mars missions to date have been one-way, so they have only had to exert enough energy to climb out of Earth's gravity well and push the payload to Mars vicinity. Once the robotic payloads arrived at Mars, they "fell" into the Mars gravity well, often bypassing orbit capture, with additional energy expended to slow down for a soft landing. Robotic missions are afforded the option to bypass orbit capture and decelerate while following a direct path to the surface because they can withstand more force during the "fall" into Mars' gravity well and they typically do not have to rendezvous with anything in Mars orbit prior to descending to the surface.

The first part of a round-trip human Mars mission is similar to a one-way robotic mission: the crewed vehicle and cargo need to escape Earth's gravity well, transit to Mars, capture into the Mars gravity well, and then de-orbit to initiate the "fall" to the Martian surface — with a little bit more energy expended to slow down for a softer landing on the Martian surface. However, unlike the one-way robotic missions, the humans need to return to Earth. To do this, they will need enough energy to climb back out of the Mars gravity well, push the crew, their return cargo, and their vehicle back to Earth, and then capture back into Earth's gravity well. This means more than double the amount of energy is needed for a human Mars surface mission compared to a one-way robotic mission.

Figure 3 shows the mass impact of traversing 1 kg of payload from Earth launch through a full round-trip mission versus delivering 1 kg of payload from Earth launch to the Martian surface. For the round-trip mission, ascent from the Martian surface is a mass driver that ripples through the earlier stages of the mission.

Gear Ratios

The mass required to launch any given payload out of Earth's gravity well, transport it to Mars, slow it down, descend, and land it on Mars is a mass multiplier, sometimes called a "gear ratio." This ratio provides a numerical representation of climbing in and out of planetary gravity wells. Gear ratio is defined as the change in the initial mass of the vehicle when a unit of payload (inert mass) is added. In other words, how much more mass is needed to deliver 1 additional kg of mass to a given point in the journey.

The relationship between the initial and final mass of a spacecraft is a function of ΔV ("delta V," the change in the velocity of the spacecraft to modify its kinetic energy), specific impulse of the propulsion system (how efficiently the propellant is converted into thrust), and propellant mass fraction (proportion of the vehicle mass that is propellant). Gear ratio will grow exponentially as the propellant mass fraction increases. Missions with higher energy requirements, like short-duration crewed surface missions to Mars, will have higher propellant mass fractions, and therefore higher gear ratios, than a Mars science payload performing a one-way, conjunction-class transit.

Gear ratio can be a convenient back-of-the-envelope multiplication factor to estimate propellant requirements or provide insight into the relative difficulty of a mission. A gear ratio will provide more straightforward insight for missions that utilize a single vehicle than it would for a complex mission with several propulsive elements.

Many architectures split propulsive responsibility between several elements to maintain their individual masses within feasible limits. For multi-element architectures, gear ratio applicability is limited to the mission phases for which an element is actively providing the propulsion.

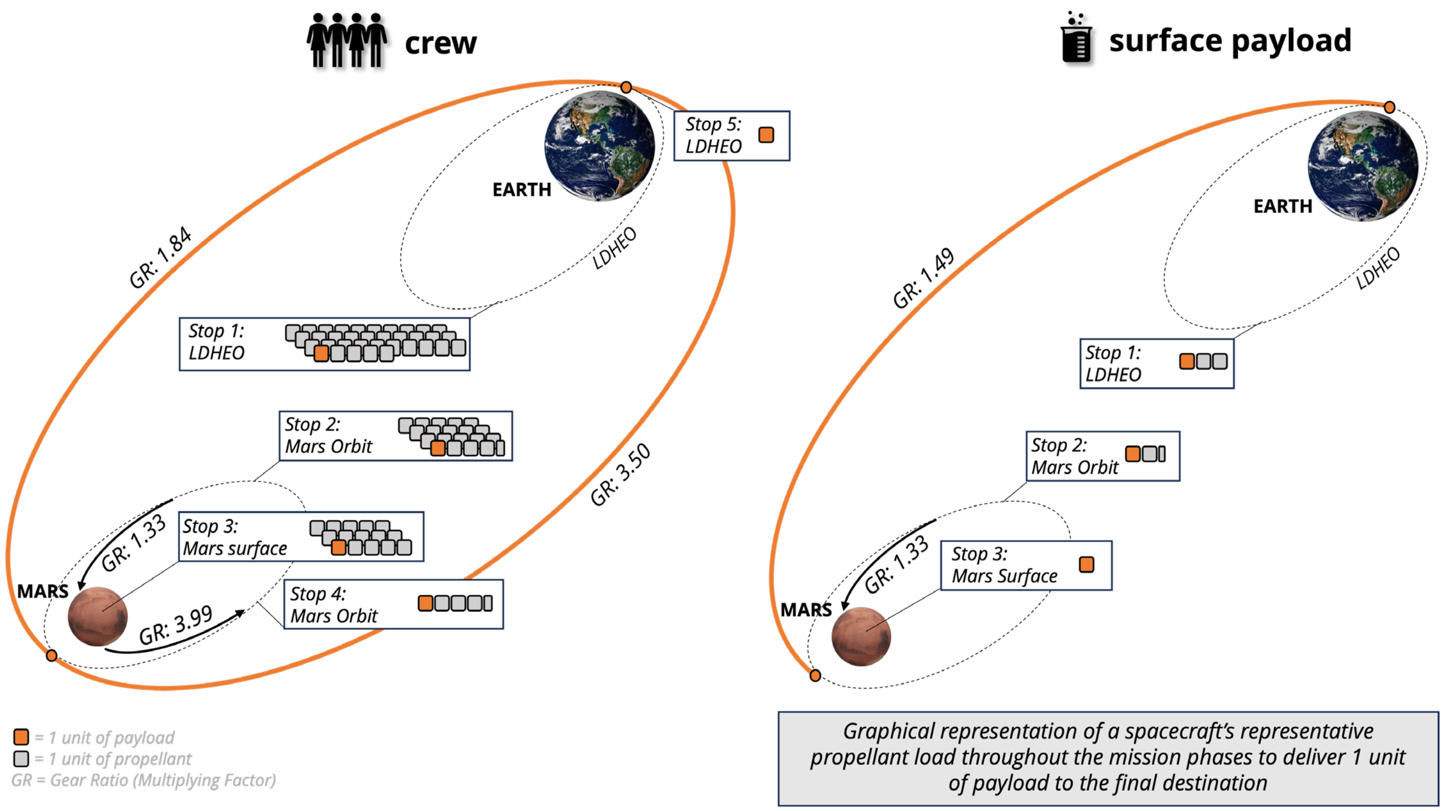


Figure 3. *Mass Impact of Delivering 1 kg of Payload Round-Trip vs. One-Way*

Additionally, many architecture elements duplicate mission phases, such as a cargo vehicle pre-positioning a lander and a later crewed vehicle that would both individually complete Earth departure and Mars orbit capture, leading to a compounding effect when looking for a whole architecture perspective.

If the mission involves manufacturing Mars ascent propellant on Mars, that propellant is not "free." The equipment needed to manufacture Mars ascent propellant will originate on Earth, so the full "cost" of that Mars ascent propellant will have to account for the mission mass required to launch the propellant manufacturing equipment out of Earth's gravity well, push it to Mars, then slow it down at Mars so it can descend and land, adding to the gear ratio.

Although a gear ratio can give insight into how inert mass added to a spacecraft can impact mission mass, it is a highly variable value that depends on mission parameters and spacecraft performance. Different missions across an architecture can have different gear ratios, which will reflect the varying mission parameters and spacecraft characteristics necessary to accomplish different missions.

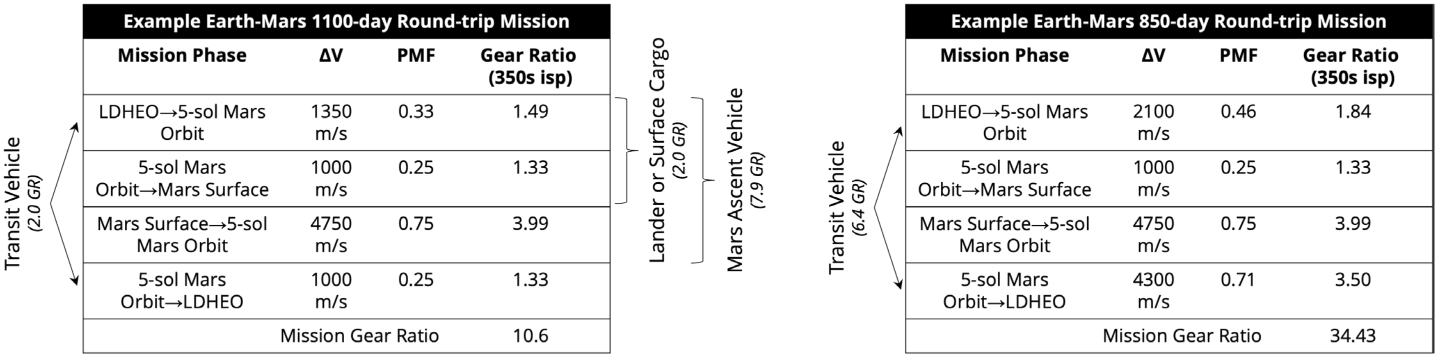
Comparing gear ratios can provide an idea of the relative propulsive difficulty required to accomplish different missions with the same propulsion system or the relative efficiency of different propulsion options when comparing them for a similar mission, such as the example 850-day round-trip mission. However, gear ratio should not be used as a stand-alone metric by which to assess architectures, as it does not convey the full scope of what an architecture is attempting to accomplish. Bringing more people or infrastructure to the surface of Mars will result in an architecture with a higher gear ratio than a science mission, but also adds capabilities to meet expanded surface objectives.

Mass Multiplier Case Study

Gear ratios can be computed for each phase of a mission and show the initial mass required to move 1 kg of payload through that phase. Multiplying gear ratios for each phase results in the full gear ratio, or mass multiplier, for a given mission.

Figure 4 provides two example cases that show the full mission gear ratio for an 1,100-day Earth-Mars round-trip mission (left) versus an 850-day Earth-Mars round-trip mission (right). For a single vehicle to complete the entire end-to-end 1,100-day mission would require approximately 10.6 kg of propellant mass for each kg completing the full round trip from LDHEO departure through return. Comparatively, an 850-day moderate-duration round-trip mission has a full mission gear ratio of approximately 34.4, about 3 times that of the 1,100-day conjunction-class mission.

When compared with the relatively small gear ratios required to land payload on the surface, these large round-trip gear ratios make using a single vehicle



Example Earth-Mars 1100-day Round-trip Mission			
Mission Phase	**ΔV**	**PMF**	**Gear Ratio (350s isp)**
LDHEO→5-sol Mars Orbit	1350 m/s	0.33	1.49
5-sol Mars Orbit→Mars Surface	1000 m/s	0.25	1.33
Mars Surface→5-sol Mars Orbit	4750 m/s	0.75	3.99
5-sol Mars Orbit→LDHEO	1000 m/s	0.25	1.33
	Mission Gear Ratio		10.6

Example Earth-Mars 850-day Round-trip Mission			
Mission Phase	**ΔV**	**PMF**	**Gear Ratio (350s isp)**
LDHEO→5-sol Mars Orbit	2100 m/s	0.46	1.84
5-sol Mars Orbit→Mars Surface	1000 m/s	0.25	1.33
Mars Surface→5-sol Mars Orbit	4750 m/s	0.75	3.99
5-sol Mars Orbit→LDHEO	4300 m/s	0.71	3.50
	Mission Gear Ratio		34.43

Figure 4. *Gear Ratios for 850-Day and 1,100-Day Crewed Round-Trip Mars Missions*

without any prepositioned components (such as return propellant, a lander, or an ascent vehicle) a challenge. Mission designs frequently split the crewed mission, and its gear ratio, between multiple components to limit the mass of any one element — for example, a transit vehicle for moving between Earth and Mars gravity wells, a lander to descend to the surface, and an ascent vehicle with prepositioned propellant to return from the Martian surface to orbit.

Key Take-Aways

Gravity well depth and the distance and desired transit time between gravity wells influence the total Earth-launched mission mass required for a particular payload.

Though it is tempting to extrapolate lunar transportation system costs to Mars applications, the Mars gravity well is deeper, and much farther away, than the Moon's gravity well, so the "cost" of a lunar architecture used at Mars cannot be directly translated without significant additional engineering analysis.

A given mission's total Earth-launched mass is often used as an analog for cost and can be useful in assessing the relative cost per kilogram of a given mission, as mission assumptions vary.

Gear ratios can provide insight into how inert mass added to a spacecraft can impact initial mass, but vary significantly based on mission parameters and spacecraft performance. They should not be used as a stand-alone metric by which to assess mission architectures, as they do not convey the full scope of what an architecture is attempting to accomplish.