The Case for Investing in Infrastructure for Affordable Space Launch

Philip Swan
The Atlantis Project
philswan@project-atlantis.com

The importance of infrastructure, such as bridges, tunnels, roads, railways, and the Internet is self-evident today, but it was not always so. Infrastructure for space launch is equally important yet no more self-evident today than the need for a globe-spanning internet was in 1980. Three primary reasons are discussed as to why humanity is not funding research into space infrastructure to the same degree that it is funding, for example, nuclear fusion. The first reason is that some stakeholders may believe the space launch services market is too small to justify infrastructure investment. The second is a public misconception concerning the rate of progress being made in reducing the cost of launch systems based on chemical rockets. The third is that too few stakeholders understand the technical feasibility and spin-off benefits of a well-considered infrastructure-based approach. This paper estimates the future value of the space launch market, analyzes the true cost of launch services today using chemical rockets, and considers the technical and economic feasibility of a largely infrastructure-based approach to space launch.

Anticipated Market Growth for Space Launch Services

The natural barriers to growth in the market for space launch services are easy to understand. These include obstacles such as the Earth's atmosphere, planetary gravity wells, the vast distances between planets, and cosmic radiation. These obstacles make it difficult for smaller entities to establish beachheads in space and then grow organically. For example, as many as 60 space mining startups are exploring various tactics for establishing a beachhead in space, but some of the earliest pioneers in this market have already failed, such as Planetary Resources and Deep Space Industries. Nevertheless, many more companies are lining up to be the first to succeed. Similarly, several early attempts to dig a tunnel between France and England failed as well. History teaches us that humanity will keep trying and will eventually prevail.

The microeconomics of how companies establish a beachhead in a new market is a very misleading way to gain an understanding of the market's ultimate potential. Consider, for example, a hypothetical company back in 1980. Let's suppose they estimate the cost of installing an underwater cable between their headquarters in Silicon Valley and a major satellite office in Japan. This idea probably would not make economic sense because the distances are vast and the amount of communication between the two offices does not justify the expense. However, if several companies pooled their resources and built a shared cable, then it might make economic sense. At a sufficiently large scale, undersea cables make terrific economic sense. Today, if we divide the total length of all the undersea cables making up the internet by the number of people on the planet, we arrive at a paltry value of only 16cm of undersea cable per person. To understand the potential future value of the launch services market, it is best to look past the tactics used to bridge the natural barriers and consider what the market will look like after the barriers fall.

Some people feel that no place, other than Earth, is sufficiently hospitable to humans. They feel that this presents an insurmountable barrier to colonization. This is unlikely to be true in practice. To appreciate this, first, consider how much time the average person on Earth already spends indoors or inside a vehicle. In North America and Europe, people are indoors roughly 90% of the time. In the United Arab Emirates, it can be more like 99.9% indoors for some people. Of the roughly 10% of the time spent outdoors, much of this time is spent within a relatively small, enclosed space, such as a garden, yard, or small park. Indoor spaces and small enclosed outdoor spaces can easily be replicated on another planet.

But what about the remaining outdoor time? Many feel that life on another planet would be psychologically untenable if the population was not able to really venture outdoors some of the time. Let's consider, for example, the difference between a ski holiday on Earth and a ski holiday on Mars. With a reasonable degree of technological advancement, the difference in bulkiness between the snow suits people wear today on Earth and the environmental suits that they would need to wear on the snow-covered slopes of a Mars ski resort is likely to be small. Of course, this assumes an *outdoor* Mars ski resort as opposed to an *indoor* facility, like one of the 121 indoor ski areas we currently have on Earth.

A popular hiking trail on Earth (see Figure 1) will typically include suspension bridges, tunnels, boardwalks, stone steps, and restrooms. A similar trail on Mars is likely to also include all of these plus an inflated transparent tube so that hikers can breathe while they are hiking the trail. Hiking trails on Mars would be slightly more complex to engineer but not difficult to imagine.

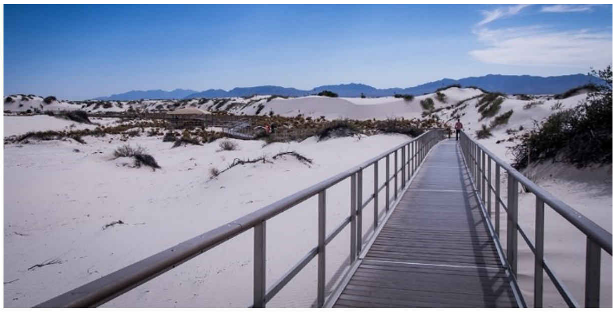

Figure 1: A hiking trail on Earth.

Compared to the Earth, Mars will be able to sustain its economy with fewer kilometers of roads and rail because, without oceans, the land area of Mars is more compact than on Earth. Fewer bridges and tunnels will be needed because there are no oceans, lakes, or rivers on Mars. Those bridges that are built on Mars will be less costly to construct than on Earth because of Mars' lower gravity and much gentler worst-case wind shears. All transportation infrastructure on Mars will be cheaper to maintain because, without precipitation, far less corrosion and erosion will occur. There are also fewer natural hazards such as earthquakes, hurricanes, tornadoes, floods, wildfires, and volcanoes on Mars. In contrast, a study from the University of Colorado, Boulder, found that about 57% of infrastructure established in the United States is threatened by natural hazards[1].

When considering human colonization, one must also consider how much we will come to rely on robots and machines equipped with various degrees of autonomy[2]. Machines controlled remotely by humans may do much of the outdoor work in inhospitable places, much as military drone operators do today. In the future, with more advanced headset technologies, the operators of humanoid robots and other machines, immersed in a very vivid telepresence experience, may experience the psychological benefits of venturing outdoors while working within a radiation-shielded facility.

Investment in technologies with long-term time horizons and highly anticipated rewards is not without precedent. The pursuit of commercially viable nuclear fusion began in 1951 and currently receives around several billion USD per year in government and private funding[3][4]. Clearly, many people believe that our energy future will be more secure if we can master this technology. Similarly, a civilization that has succeeded in expanding out into the solar system will be more secure than a civilization that is isolated on Earth. For example, consider the value of having Mars achieve a level of prosperity (measured on the basis of USD generated per km^2 of land area) similar to what we achieve on Earth today. The worldwide Gross Domestic Product (GDP) of Earth was 96.5 trillion USD in 2021. Mars' land area is 144.8 million km^2 compared to Earth's 510.1 million km^2; therefore, the Mars economy would contribute…

$$\begin{aligned} GDP_{Mars} &= GDP_{Earth} \cdot \frac{LandArea_{Mars}}{LandArea_{Earth}} \\ &= 96.5 \cdot \frac{144.8Mkm^2}{510.1Mkm^2} \\ &= 27.3\ trillion \frac{USD}{year} \end{aligned}$$

…towards the human civilization's GDP. Of course, Mars isn't the only place where human civilization is likely to establish its economic engines. Other planets, moons, and asteroids in the solar system are likely to be developed as well.

The belief that the market for space launch services is too small to justify infrastructure investment is certainly false in a macroeconomic sense. As with technologies such as commercially viable nuclear fusion, investors consider the technology's potential to be transformative. It is the difference in the value of the economy before and after the transformation that defines the value of the technology or technologies that enabled the transformation.

In the case of space launch infrastructure, the value of the transformation that it could bring about is the difference in value between a civilization that has successfully expanded into to solar system and the future value of the single-planet civilization that we have today. That difference is likely to be in the range of 20 to 50 trillion USD per year.

The Cost of Chemical-Rocket-Based Launch Systems

The second reason why humanity is not aggressively funding research into space infrastructure may be a widespread public misconception concerning the rate of progress being made in reducing the cost of launch systems based on chemical rockets. To understand this progress, we can compare today's costs to those in the era of the Space Shuttle.

The Space Shuttle served NASA and its partners well for many years. Its cost is generally reported by dividing the total cost of the space shuttle program by both the number of times it was launched and the amount of payload that it could deliver, per launch, to the International Space Station. If one uses this approach, then the cost-per-kg to the International Space Station (ISS) for the Space Shuttle was…

$$Cost_{PerKgToISS} = \frac{TotalProgramCost}{NumLaunches \cdot PayloadPerLaunch}$$

$$= \frac{212\ billion}{135 \cdot 16{,}050kg} = 97{,}842\frac{USD}{kg}$$

However, a more precise way to arrive at the cost is to assume that all space shuttle missions were ISS resupply missions, and then plot the total amount of payload delivered versus the amount of money that was spent on the program, using 2023 inflation-adjusted dollars.

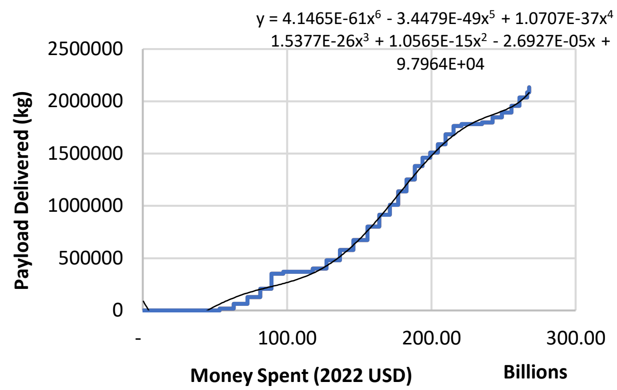

Figure 3: A graph of payload delivered by the Space Shuttle versus money spent, if hypothetically all Space Shuttle missions were deliveries to the ISS.

This approach gives us the plot shown in Figure 3. By fitting a curve to the data in Figure 3 and plotting the inverse slope of that curve versus time, we end up with the orange curve of a USD-per-kg versus year shown in Figure 2.

We can see that the Space Shuttle's cost-per-kg came down over time, but we can also see that there are a few peaks and valleys in the curve. The peaks were caused by the Challenger and Columbia disasters. Between these events, cost dipped to as low as 59,000 USD/kg.

If we apply the same methodology to Commercial ISS resupply services in general (blue curve) and the cost with

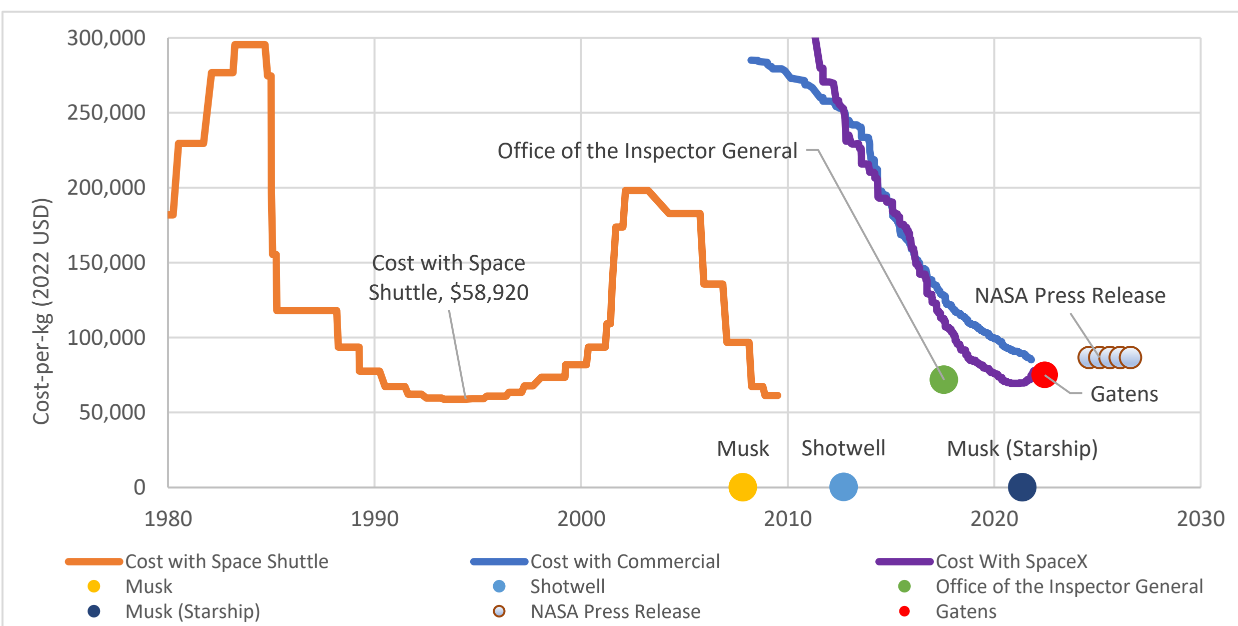

Figure 2: Launch cost-per-kg versus year. Solid dots are positioned horizontally at the time that the statements were made or published. Other data is positioned horizontally based on launch date. Lines represent data from usaspending.gov.

the market leader, SpaceX (purple curve), using data from usaspending.gov[5]–[7], we observe that in practice the costs have only recently managed to achieve cost parity with the Space Shuttle Program. A 2016 independent audit from the Office of Inspector General, on page 27, projected that the cost of commercial ISS resupply with SpaceX would be 71,800 USD/kg[8], which aligns well with the usaspending.gov data shown in Figure 2.

Other corroborating data includes an Aug 31st, 2022 press release by NASA where they announced that they had awarded five additional missions to SpaceX at a cost of $1.436 billion or $287 million per mission.[9] This places the cost of future resupply missions 10 through 14 at 1,436,438,446 USD, which works out to 86,794 USD/kg if we assume that each mission delivers the maximum payload of 3307kg to the ISS[8]. On March 8th, 2023, Robyn Gatens, Director of the International Space Station at NASA, stated informally during a Q&A session at the IEEE Aerospace Conference that half of the ISS budget goes to launch costs. As NASA spends roughly 3B per year on the ISS, and resupply runs deliver people and cargo at a rate of roughly 20,000kg per year, this works out to…

$$3B\ USD \cdot \frac{USD}{2\ \cdot\ 20{,}000kg} = 75{,}000\ USD/kg$$

In contrast to the data presented above, various aspirational statements have been made that paint a very different picture.

For example, on September 8, 2005, SpaceX announced two variants of the Falcon9, one that would cost 27 million and another that would cost 35 million.[10]

An October 21st, 2008 article[11] quoting Musk said, "However, since Falcon 9 costs only $200,000 to refuel (and reoxidize), an efficient refurbishment and launch operation would allow the production costs to be amortized over many flights. This has the potential to bring the per-launch price down to about $1 million, a hundredfold improvement over current costs. And if that happens, life will become sustainably multiplanetary in less than a century."

On June 17th, 2013, at a satellite conference in Singapore, Gwen Shotwell said, "So, if we get this right - and we're trying really hard to get this right - we're looking at looking at launches to be in the 5 to 7 million dollar range."

At a Starship Update presentation[12], streamed live on Feb 10th, 2022, Elon Musk said, "…the holy grail breakthrough that's needed is a rapid and completely reusable rocket system. So, this has never been accomplished before. And there's a lot of people for the longest time who thought this was not possible. Now with Falcon9 we have been able to show that you can have reuse of a boost stage and reuse of a fairing. So, in Falcon9 we have demonstrated a lot of reuse of the boost stage and the faring … and that's a big step in the right direction. For Starship we're aiming for full and rapid reusability.

"On a cost basis … it's a 100-ton capability to orbit.

"On a marginal cost per launch basis – that doesn't count fixed costs that obviously have to be covered – it may be as little as a few million dollars per flight. Maybe even as low as a million dollars per flight.

"We do have to cover fixed costs, so depending on what our launch rate is, we have to divide the fixed cost by the number of launches, so the more launches that happen, the lower the … fully considered cost per flight would be. But I'm highly confident that it would be less than 10 million dollars, all in, if you fast forward two or three years from now. I think it's highly likely to be – everything included – less than 10 million dollars a flight for a 100-ton-to-orbit capability. And 100 tons to a useful orbit, not a low orbit. To a low orbit, it would be 150 tons. So, this is ridiculously good compared to everything else, and it should be. If aircraft were not reusable, how much would an air ticket cost? … If you imagine we were in a world where aircraft were expendable, and then someone came along with a reusable aircraft, it would be an absolutely profound game changer. That's what needs to happen for life to become multi-planetary. This design, I'm confident, is capable of that. It's just a question of how long it will take to refine that and have it really dialed [in]."

As late as 2022 SpaceX's own datasheet [13] stated that the price per launch was 67 million, but with disclaimers that said "Pricing adjustments made in March 2022 to account for excessive levels of inflation. Missions purchased in 2022 but flown beyond 2023 may be subject to additional adjustments due to inflation" and "Performance represents max capability on fully expendable vehicle."

To recap, the most expensive data point we presented is the cost for ISS resupply quoted by NASA for resupply missions 10 through 14, which will take place between 2025 and 2027, and which is 86,794 USD/kg. The least expensive data point presented is the cost projection that Musk made in his 2022 update was that Starship where he said that launch costs would be 100 USD/kg by 2025. The lower data point is 868 times less costly than the upper data point, which represents a significant discrepancy.

Explaining the Discrepancy

The Psychology of Misinformation

The existence of a significant discrepancy indicates that there is misinformation in circulation. On the topic of misinformation, an article in the Annual Review of Political Science[14] explains it as follows: "Misinformation occurs when people hold incorrect factual beliefs and do so confidently. The problem, first conceptualized by Kuklinski and colleagues in 2000, plagues political systems and is exceedingly difficult to correct."

"In considering the causes of misinformation, it is useful to remember that "citizens bring to politics the same psychological architecture they bring to all of individual and social life" (Leeper & Slothuus 2014, p. 138). Thus, research from psychology provides a foundation for theorizing about this phenomenon and its boundary conditions. A crucial insight from psychology is that there is a general human tendency to strive toward particular end states or goals, and these motivations influence all facets of the reasoning process, from seeking out and evaluating evidence to forming impressions (Kunda 1990). Motives may come in many forms, but the contrast between accuracy and directional motives has been a fruitful dichotomy. Accuracy motives indicate a desire to make the correct decision. Directional motives, by contrast, reflect the desire to arrive at a specific conclusion, e.g., one that maintains consistency with one's attitudes. Of course, both goals can be held by the same person but be more or less influential depending on the decision-making context."[15]

The same article then says, "…to be misinformed is different from being uninformed, a state in which a person has no factual beliefs about the topic under inquiry.

"This distinction has significant normative implications insofar as the misinformed base their political opinions on inaccurate beliefs. When large segments of the public are misinformed in the same direction, shared misperceptions can systematically bias collective opinion (Kuklinski et al. 2000), undermining the idea that "errors" in individual-level preferences cancel out in the aggregate (e.g., Page & Shapiro 1992). Even more worrisome is the prospect that misinformed people take political action on the basis of incorrect information, becoming what Hochschild & Einstein (2015) call the "active misinformed."

It is quite plausible that, in the present information age, there is a mix of both "accuracy-motivated" and "directionally motivated" people who are creating and circulating much of the content we see on the Internet.

Space Agencies Versus Commercial Entities

Space agencies, such as NASA, and other government departments, such as the Department of Defense, are required to report their spending on usaspending.gov. Independent oversight organizations such as the Office of Inspector General perform audits that help to improve the accuracy of publicly available information. Commercial entities do not operate under the same constraints; therefore, it is generally more difficult to formally verify the information that they produce. Other information, such as the final price that each customer actually paid for a launch, is simply kept confidential and never made public.

Marketing and Orbital Mechanics

When promoting a product or a service, the goal is to make that product or service appear as good as possible. This generates excitement, which drives rapid information dissemination by word-of-mouth and helps to attract investment. One way to achieve this is to assume the easiest possible mission profile, a so-called "marketing" mission profile.

A recent article on launch costs[16] states "The maximum payload capacity to LEO for a space launch vehicle is simply the highest mass capacity reported by a launch provider. Often, the maximum payload capacity is calculated by assuming a relatively low-altitude circular orbit, such as 185 km, and an inclination that corresponds to the latitude of one of the vehicle's preferred spaceports. If the same space launch vehicle were to support a different mission to LEO, such as one that requires a higher altitude or inclination, the payload capacity would be reduced."

For example, SpaceX's Capabilities and Services datasheet [13] says that Falcon 9 can launch 22,000kg to low Earth Orbit with their non-reusable configuration, but they quote prices for their reusable configuration. A "heaviest payload ever flown" record of 17,237 kg was set for Falcon9 according to a Jan 2023 article by Spaceflight Now[17]. This was for a Starlink launch. Starlink satellites, however, are equipped with ion thrusters which they use to raise their orbits from their insertion orbit to their operational orbit. In comparison, when Falcon9 and Dragon 2 are used together to resupply the ISS, the maximum pressurized upmass is 2507kg and the maximum unpressurized upmass is 800 kg, for a total of only 3307 kg[8].

Mixing reusable configuration prices with non-reusable configuration payloads is not the primary mechanism by which misinformation about costs is created. The desire to paint one's product in the best possible light has the undesired consequence of leading people to believe that launch costs came down when in fact the nature of the reference mission was changed. The baseline mission and costs established during the shuttle era involved ferrying crew, provisions, and scientific experiments to and from the ISS. The reported lower costs used in recent marketing materials are associated with an easier and thus less costly mission, that is, launching satellites equipped with their own onboard thrusters to the most easily accessible and lowest viable altitude orbit.

The difference between a satellite launch-to-LEO mission and an ISS resupply mission is not just the altitude and inclination of the orbit. ISS resupply missions involve sending a life-sustaining reentry-capable vehicle to orbit along with the payload. That vehicle needs fuel to deorbit, a heat shield to decelerate the vehicle, and either wings or parachutes to land it softly. All of these eat into the mass budget leaving less and less mass available for the "real payload", comprising of crew, supplies, experiments, replacement parts, etc.

When comparing a new system, such as Falcon 9 paired with Crew Dragon, to a past system, such as the Space Shuttle, it is important to use a mission class that both systems were designed to support as the basis for fair comparison.

Circular Reporting (aka, the "Woozle Effect")

Another source of error is that early and aspirational cost-per-launch numbers are sometimes immortalized in early reports which are then referenced by later reports. The more forward-looking aspirational values tend to be significantly lower than numbers arrived at with the benefit of hindsight. Incidentally, this phenomenon also occurred during the early days of the Space Shuttle program.

Circular reporting is perhaps a side effect of content creation for platforms such as YouTube, where the most successful content creators produce and upload videos frequently and consistently. When compared to their predecessors who created content primarily for television networks, this new breed of content creators may not be able to spend as much time doing extensive in-depth research and fact-checking.

For example, on June 23rd, 2022, a popular YouTuber released an ask-me-anything style episode entitled "Is SpaceX REALLY Bringing Down Launch Costs?"[18]. In it, he displayed a chart from another site called "The Visual Capitalist"[19]. That article cited its source as the Center for Strategic and International Studies (CSIS) – likely a September 1, 2022 article entitled "Space Launch to Low Earth Orbit: How Much Does It Cost?"[20]. This article includes a high-quality interactive visualization which helps to bolster its apparent credibility. In that visualization, the source for the Falcon9 data is a report from the FAA Office of Commercial Space Transportation[21] written in 2018. That FAA report states on page 3, "Publication produced for FAA AST by Bryce Space and Technology under contract." On page 17 of the report, there is a table with the heading "*Estimated* Price Per Launch" (see Figure 4), which basically indicates that the values in the column are estimates - no other source was cited.

The estimated values are the same in nearly identical tables published in earlier versions of the FAA report produced in 2016 and 2017. (Note, The 2016 report was created under contract by The Tauri Group, which was renamed in 2017 according to this tweet: https://twitter.com/BryceSpaceTech/status/839188943103004673?s=20). It seems reasonable to assume that the original estimate for the price of a Falcon9 launch was made in 2016.

Vehicle	Operator	Year of First Launch	Total 2015 Launches	Active Launch Sites	Mass to LEO kg (lb)	Mass to SSO kg (lb)	Mass to GTO kg (lb)	Estimated Price per Launch
Antares	Orbital ATK	2013	0	MARS	3,500-7,000 (7,716-15,432)	2,100-3,400 (4,630-7,496)	N/A	$80M-$85M
Atlas V	ULA and LMCLS	2002	9	CCAFS VAFB	**8,123-18,814 (17,908-41,478)**	6,424-15,179 (14,163-33,464)	3,460-8,900 (7,620-19,620)	$110M-$230M
Delta IV	ULA	2002	3	CCAFS VAFB	9,420-28,790 (20,768-63,471)	7,690-23,560 (16,954-51,941)	3,060-14,220 (6,746-31,350)	$164M-$400M
Falcon 9	SpaceX	2010	7	CCAFS VAFB	13,150 (28,991)	Undisclosed	4,850 (10,692)	$61.2M
Minotaur-C	Orbital ATK	2016	0	CCAFS MARS VAFB WFF	1,278-1,458 (2,814-3,214)	912-1,054 (2,008-2,324)	N/A	$40M-$50M
Pegasus XL	Orbital ATK	1994	0	CCAFS Kwajalein VAFB WFF	450 (992)	325 (717)	N/A	$40M

Table 1. Orbital vehicles currently available for commercial use by U.S. providers.

Figure 4: Table from the 2016 report entitled "The Annual Compendium of Commercial Space Transportation"[21]

In summary, in this case study a very well-respected YouTuber told his followers in 2022 that the launch prices are going down, based on a launch cost estimate that was made back in 2016, and that was merely "an estimate" in the originally sourced report. In the field of journalism, this is a clear example of a phenomenon known as "The Woozle Effect"[22], or "evidence by citation".

Using old data is not the only inaccuracy in the chain of references described above. If we take the original source values (61.2M USD_{2016} per launch and 13,150 kg per launch) and correct for inflation to the year 2023 (a factor 1.26[23]) then we arrive at a cost of 5,906 USD_{2023} per kg. The 2022 CSIS article published a value of 2,600 USD_{2022}-per-kg), a value 54% lower than the value we arrived at by using the source they referenced, without providing any explanation.

The "The Visual Capitalist" article[19] includes additional points for Falcon Heavy ($1,500) and Starship ($200) which helped to create the appearance of a steep downward trend in costs. If Falcon Heavy were cheaper than Falcon9 as the chart suggests, then one would expect SpaceX to use Falcon Heavy to launch its Starlink satellites. In practice, the Falcon Heavy may be less reusable than the Falcon9 because the Falcon Heavy has not yet demonstrated the ability to land its core stage downrange on a drone ship. SpaceX's actions may reflect an internally held belief that using Falcon Heavy would be more expensive than using Falcon 9 for launching Starlink satellites.

The published Starship estimate of 200 USD_{2022} per kg by the year 2024 is, of course, a forward-looking and aspirational data point.

The Techno-Economic Feasibility of Infrastructure-Based Launch

There are many definitions of infrastructure, but, in the context of this discussion, we will define it as building something that will fundamentally change the economics of launching payloads into space.

The cost of launching chemical rockets is fundamentally limited by the physics of the Rocket Equation

$$m_0 = m_f\, e^{\Delta V / V_e}$$

where:
'm_f' is the final mass of the payload ($m_{payload}$) plus the dry mass of the rocket (m_{rocket}),
'ΔV' is the change in speed,
'V_e' is the exhaust velocity of the rocket's engine(s), and
'm_0' is the initial takeoff mass of the rocket, including the rocket's dry mass, its propellant, and its payload.

Many years of research and development have been invested to increase the exhaust velocity and reduce the dry mass of a rocket.

However, the payload fraction, the ratio of delivered payload mass to initial mass, m_0, remains quite low. For example, Table 1 shows an estimated mass allocation for Falcon9 + Crew Dragon when configured to resupply the ISS. The payload fraction in this case is only 0.006189, or roughly 1/162. To help put this in perspective the payload fraction for an aircraft is closer to 0.5. The payload fraction for a Crew Dragon returning from the ISS is around 0.19 (From Table 1 in [8]).

Table 1: Falcon 9 plus Crew Dragon Component Masses

Component	**Mass(kg)**
First Stage Dry Mass	25,600
Second Stage Dry Mass	3,900
Trunk Dry Mass	2,905
Crew Dragon Dry Mass	7,700
First Stage Propellant	395,700
Second Stage Propellant	92,670
Crew Dragon Propellant	2,562
Payload (Upmass to ISS) [8]	3,307
Total Takeoff Mass	534,344
Payload Fraction	0.006189

Defeating the rocket equation, even to a small degree, requires heroic engineering. Observe that the Falcon 9's first-stage dry mass is only 6% of its total mass. The second stage dry mass is even better – only 4% of its total mass. On the metric of lifting the largest multiple of its own dry mass, a rocket significantly outperforms an airplane.

The possibility of further research on chemical rockets yielding a significant improvement to either the dry mass fraction or exhaust velocity (while maintaining safety) seems remote. However, by using an infrastructure-based approach we can significantly reduce the delta-v required to reach a destination, such as a rendezvous with an orbiting space station.

Several concepts have been proposed that take this approach. Some, such as Spin Launch, use a mass driver installed on Earth to partially accelerate the vehicle before the rocket takes over. Others, such as momentum exchange tethers, attempt to rendezvous with a vehicle after it reaches an orbital altitude while traveling on a ballistic trajectory. Let's first examine the benefit of offloading some of the delta-v requirements from the rocket to an infrastructure element.

Let's assume that the infrastructure is an earth-based launch system comprising three elements (see Figure 1):

1) A mass-driver housed within an evacuated tube, submerged 100m below the surface of the ocean,
2) An upward-curving tunnel drilled from the coast to the summit of a mountain, and
3) An evacuated tube supported by a latticework of girders or a combination of dirigibles and guy wires.

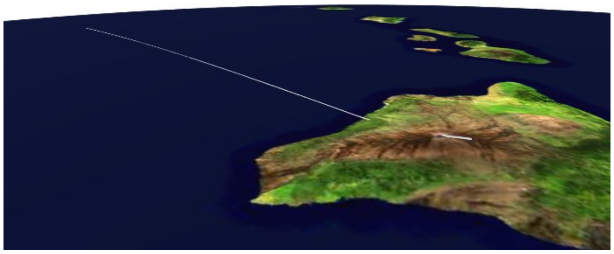

Figure 5: Mass driver, tunnel, and evacuated tube.

This system will launch a vehicle equipped with a rocket engine; that engine is fired only after the vehicle exits the evacuated tube. An airlock with fast doors at the end of the tube allows the vehicle to exit but keeps air from flowing in, helping to maintain the vacuum in the tube.

To produce the charts shown below, a system of this type was simulated while varying two design parameters: 1) The mass driver's exit speed, and 2) The altitude at the end of the evacuated tube. The curvature of the tunnel and the roll program for the vehicle were optimized automatically for each run.

In each case, the launch system boosted an aerodynamic vehicle equipped with a single RS-25 engine - the main engine used by the Space Shuttle and SLS rocket core stage. After receiving the boost, the vehicle was required to use this engine to achieve a circular orbit at the altitude of the ISS (420km).

The results of the parametric study are shown in Figures 6 through 10. Figure 6 shows that the more boost the launch system provides, the less delta-v the rocket must provide. It also shows that the benefit of the evacuated tube (in terms of helping to reduce the amount of delta-v we need the rocket to provide) is small when the mass driver exit speed is below 6000 m/s.

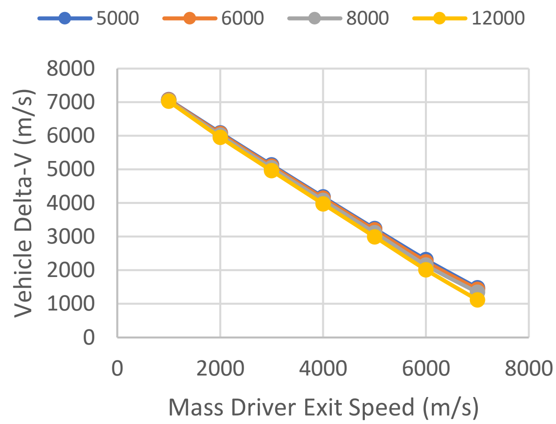

Figure 6: Delta-v imparted by the vehicle's rocket engine for four different altitudes of the evacuated tube.

Figure 7 shows the relationship between mass fraction and the varied design parameters. Recall that the mass fraction is the ratio of the rocket's initial mass (vehicle, payload, and propellant on the pad) to its "final mass" (vehicle and payload and any leftover propellant). The "Final Mass" term in the rocket equation is perhaps a bit of a misnomer. It was, of course, defined in a time when rockets were not recovered and reused. In the rocket equation, Final Mass, or m_f, is simply the mass of the rocket when it has finished imparting delta-v to its payload. For example, the final mass of a first-stage booster is typically its mass at the time when it separates from the second stage. The "payload" in this case of the booster would be the second stage and its propellent, the orbiter, and any crew, provisions, fuel, etc. within the orbiter.

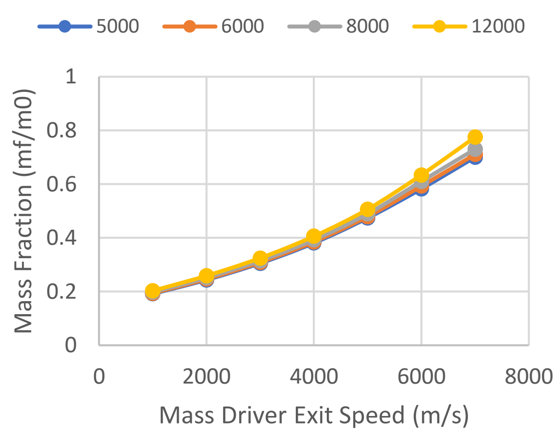

Figure 7: Mass fraction versus mass driver exit speed for four different evacuated tube exit altitudes.

Because launch costs are driven more by the cost of the hardware than the cost of the propellant, a more interesting ratio is the payload-to-rocket-hardware mass ratio, which is the ratio of the mass of the payload to the mass of the hardware that was needed to launch it. To estimate this ratio, we must assume an engineering-limitations-driven relationship between the dry mass of the rocket and the mass (and volume) of the propellant and payload contained within it. For example, let's assume that a rocket can be engineered to weigh as little as 8.1% of the mass of the propellant and payload that it carries based on the numbers in Table 1. Let's call this value 'E'. With this assumption, we can convert the mass ratio to a payload-to-rocket-hardware ratio as follows

$$m_f = E(m_0 - m_f + m_p) + m_p \quad (1)$$

$$m_p = m_f - E\,m_0 + E\,m_f - E\,m_p \quad (2)$$

$$m_p + E\,m_p = m_f + E\,m_f - E\,m_0 \quad (3)$$

$$(1+E)\,m_p = (1+E)\,m_f - E\,m_0 \quad (4)$$

$$m_p = m_f - \frac{E}{(1+E)} m_0 \quad (5)$$

$$m_r = m_f - m_p \quad (6)$$

$$m_r = m_f - (m_f - \frac{E}{(1+E)} m_0) \quad (7)$$

$$m_r = \frac{E}{(1+E)} m_0 \quad (8)$$

$$\frac{m_p}{m_r} = \frac{m_f - \frac{E}{(1+E)} m_0}{\frac{E}{(1+E)} m_0} \quad (9)$$

Where the subscripts on the mass variables (the m's) are for "rocket", "payload", "final", and "initial" mass, where initial mass is indicated with the zero subscript.

If we divide the numerator and the denominator on the right side of the equation by m_f, we get…

$$\frac{m_p}{m_r} = \frac{1 - \frac{E}{(1+E)} \frac{m_0}{m_f}}{\frac{E}{(1+E)} \frac{m_0}{m_f}} \quad (10)$$

Note that m_0/m_f is the mass ratio.

Using this equation and plugging in a sample value of E=0.081, allows us to estimate the payload-to-rocket-hardware ratio.

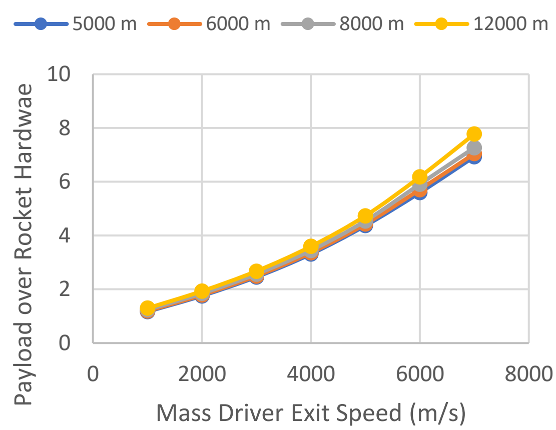

Figure 8: Relationship between the payload mass and the mass of the rocket hardware used to place the payload in orbit.

This graph shows that using infrastructure to boost the vehicle improves the amount of payload that can be launched at a rate that is better than proportional to the exit speed of the mass driver.

The next consideration is whether the launch system would subject the payload to very high gee forces that would limit the utility of the system.

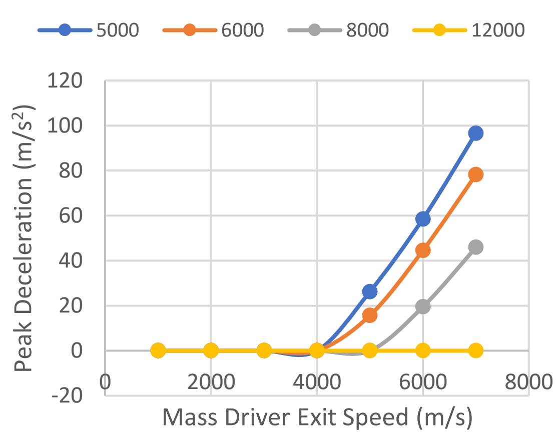

Figure 9: Peak deceleration due to atmospheric drag.

Figure 9 shows the peak deceleration that the simulated vehicle experiences due to atmospheric drag. In most cases the rocket's thrust exceeds the deceleration due to atmospheric drag leading to only "eyes-in" forward acceleration. However, if the vehicle is launched too fast and too low in the atmosphere aerodynamic drag will be greater than the maximum thrust of the rocket leading to some amount of "eyes-out" acceleration, or deceleration. The third component of the launch system, the suspended evacuated tube, is helpful in mitigating this effect. It is not the only solution, however. A higher thrust rocket engine or techniques for protecting the payload (such as crew) from the brief eyes-out gee forces can also serve. Note that the highest point in Figure 9 is 10 gees, which is a force that occurs for only a few seconds before quickly abating.

Interestingly, the lateral gee forces that occur in the tunnel, although brief, are more significant in some of the design configurations. A longer and higher altitude evacuated tube will allow the vehicle to launch at a lower angle of attack which reduces the amount that the tunnel needs to bend the vehicle's trajectory upwards. This is an area where more work needs to be done exploring the best design trade-offs.

Another area of concern is the thermal protection system. In the case of the launch system designs used in the parametric study, the thermal loads are in some cases intense, albeit very brief, in duration.

Another challenge concerns the cost of the mass driver. Railgun rails have proven to have reusability challenges, at least when the application involves using them to launch shells from a ship. Coil guns have challenges associated with rapidly turning on and off the electromagnets. This is a challenge that is potentially addressed with a quench gun-type design, where the electromagnets are turned off rapidly by "quenching" their superconductivity sequentially as the vehicle passes by.

A new approach that might prove more economical involves the use of variable-pitch high-speed screws[24].

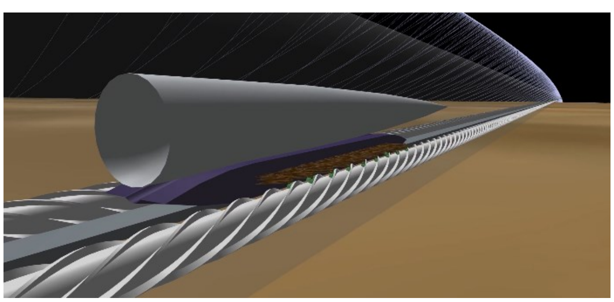

Figure 10: Launch vehicle on a launch sled.

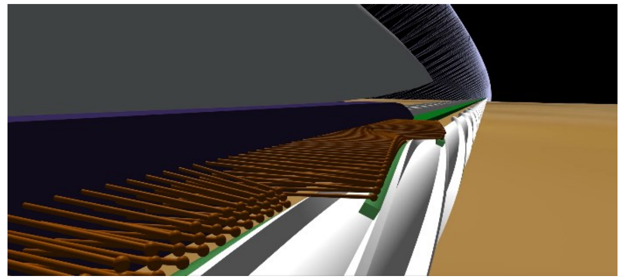

Figure 11: Grapplers (green) attached to the sled by struts (orange) magnetically couple to the leeward side of the screws' threads.

This system uses magnetic coupling without rapidly switching off electromagnets or quenching the conductivity of superconducting electromagnets.

Conclusions

Research into space infrastructure has the potential to be transformative in terms of advancing humanity from a single planet to a multi-planet civilization. The future value of such a transformed civilization is enormous, perhaps even more significant than a civilization that has successfully made the transition to 100% renewable energy. Technologies that will truly help to bring about such a transition are worthy of significant investment.

However, we must think critically about how the rate of advancement of some technologies is being marketed to the public, politicians, and investors. In the case of chemical rockets, there are widespread misconceptions about the rate of progress being made. These misconceptions are arrived at by comparing new systems to legacy systems inaccurately, for example, by comparing information gained in hindsight from a government oversight agency to one or more aspirational and forward-looking statements of a new launch system's proponent. Another example is to compare two systems with the new system using a much easier class of mission than was used to characterize the legacy system. When compared properly on an apples-to-apples basis, using a common mission class, and when properly accounting for inflation, the newest reusable launch systems are shown to be slightly more expensive than a legacy system such as the Space Shuttle.

Infrastructure-based approaches to launch have the potential to change the economics as they can break us free of the limits imposed by the physics of the rocket equation. The parametric studies reported in this paper indicate that a properly architected earth-based mass driver is an example of such a technology. They also show that atmospheric drag is not a serious impediment to implementing this approach.

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