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The Future Impact of Much Lower Launch Cost

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For decades, the high cost of space launch has been the greatest limiting factor on the number and size of space missions. Recently commercial rockets have reduced launch cost to about one-twentieth of the space shuttle cost. This provides opportunities for a matching reduction in the cost of space systems and more and more massive missions. High launch costs greatly increase the cost of developing space systems, since the need to reduce mass forces the use of light materials, high packaging densities, and fragile structures that are difficult to manufacture and test. Lower launch costs allow the use of more robust and well tested off-the-shelf systems. Increased mass can be used to increase single string reliability and also to provide spares and redundancy. A crewed mission can benefit from lower launch costs by using mass to provide more accepted fully hydrated food, additional hygiene water, laundry, radiation shielding, and even artificial gravity. The crew can be made healthier, safer, more comfortable, and more productive. Lower launch cost makes every space activity easier, whether it is science, human exploration, commercial including communications, weather, surveillance, and geo-positioning services, or the defense of similar military services. Most of the solar system is empty space, with the energy of the sun's radiation passing through to the cold of deep space. The missing mass needed to support human activities is now much easier to provide.

Nomenclature

ACES = Advanced Cryogenic Evolved Stage
BFR = Big Falcon Rocket
FAA = Federal Aviation Administration
GEO = Geosynchronous Earth Orbit
ISS = International Space Station
LEO = Low Earth Orbit
ULA = United Launch Alliance

I. Introduction

THE history of the human race has been exploration, expansion, and wider spreading interaction based on improving transportation, ultimately leading to a globalization that has reached the ends of the Earth. The new lower cost of space launch will enable increased exploration, expansion and interaction in Earth orbit and cislunar space, extending through the solar system and beyond.

The cost of space launch has declined and probably will go lower. Lower launch cost has removed a major impediment to human use of space. Great projections are made for future human expansion in space. The future impact of lower launch cost will be considered over short, medium, and long time frames.

A. The cost of space launch has declined

The cost of space launch has been very high but recently it has been significantly reduced. Launch cost to Low Earth Orbit (LEO) in today's dollars dropped from a 1950's high approaching $1,000 k/kg down to a low of about $5 k/kg for the Apollo Saturn V. From 1970 to 2010 launch cost to LEO was usually between 10 and 20 $k/kg in today's dollars. Soviet and Chinese costs were somewhat lower and the space shuttle much higher at 62 $k/kg to LEO. (Wertz and Larson, 1996, p. 115) (Wertz and Larson, 1999, p. 802) (Jones, 2018-81) In 2010, the Falcon 9 reduced launch cost to LEO to $2.7 k/kg. The recently demonstrated Falcon Heavy reduces it by half to $1.4 k/kg. (SpaceX.com, 2018) (Jones, 2018-81) The cost of launch to LEO has been reduced by a factor of 10 or 20.

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Launch cost will probably go lower for several reasons. SpaceX has demonstrated rocket recovery and reuse, which may provide additional cost savings of 30 to 50 percent. (Morris, 2017) The expected increasing number of launches will reduce the amount of past development and current operating costs charged to each launch. The number of competitors providing rocket launch has increased and more are considering entry. (Kim, 2017)

B. Lower launch cost has removed a major impediment to human use of space

High launch cost has contributed to high spacecraft cost and high mission cost, and has inhibited new space missions. High launch costs have been "the greatest limiting factor to expanded space exploitation and exploration." (Wertz and Larson, 1996, p. 117

> "A payload budget planner must allocate such a significant portion of the budget to launch services that launch cost considerations ripple powerfully through all aspects of space mission planning. Also, the cost of a spacecraft has become strongly linked to the cost of launch, so reducing the cost of space systems and their missions depends to a large extent on achieving lower prices for space transportation." "Some estimates have indicated that high launch costs are responsible for about one-half of the total cost of new satellite systems." (Wertz and Larson, 1996, p. 117)

C. Great projections are made for future human expansion in space

Some think that lower launch cost "will change our lives." (Autry, 2017)

> "Space tourism, materials development, pharmaceutical research, power generation, communications, earth imaging and national security all have 'killer apps' just waiting for reliable and affordable access to space." (Autry, 2017)
>
> "The disruption SpaceX had caused in the launch service industry could lead to 2020s becoming the decade of reusable launch systems offering low-cost access to space. This helps create a space-based economy transforming businesses on Earth with manufacturing moving into outer space, utilizing resources mined from the celestial bodies. For Musk, it is not about just creating a new economy but helping humanity itself survive by making Mars habitable." (Reddy, 2017)

II. The future impact of lower launch cost

The future impact of lower launch cost will change and increase with time. Launch cost is only one of many factors in space mission planning. Since launch cost has been reduced, overall mission costs will be lower and more launches can be expected, but in the short term most things will generally remain the same. The same commercial, civil government, and military customers will want the same kinds of missions, use the same infrastructure, and launch familiar systems.

In the medium term, some obvious and foreseeable adjustments will probably occur. Less mass reduced, less reliable, less capable, and much less expensive payloads can be launched. Higher risk technical and commercial experiments can be made. The missions, infrastructure, and payloads can gradually adjust to a more optimal configuration that uses more space launches and less of other cost factors.

In the long term, with such a large cost change, everything can change, beyond our ability to predict. This has been repeatedly observed in the history of transportation, with the successive development of sailing ships, canals, steamships, railroads, automobiles, and aircraft. Human life has completely changed and we are now in the era of globalization. Lower space launch cost will enable future human expansion in space. National prestige, military necessity, and commercial opportunity all provide goals and motivation, but the result will probably be surprising.

The recent significant decrease in space launch costs will change operations, planning, and infrastructure, but the full effect will take considerable time. Table 1 considers these changes in the short, medium, and long term.

Table 1. Changes in space mission operations, planning, and infrastructure in increasing time frames.

	Operations	Planning	Infrastructure
Short term	More launches Current logistics, inventory, and supply chain methods Rocket recovery	More current concept missions Current deployment, rendezvous, and staging scenarios Rocket reuse	Existing launch facilities Ocean rocket landing platforms Current payloads
Medium term	More launch on demand, less on-orbit storage Supply chain optimized for low cost launch	Heavier, less expensive payloads Opportunistic mission concepts and scenarios	More launch facilities Further rocket development Lower cost space systems
Long term	Operations supporting innovative missions	Innovative mission concepts and scenarios	Infrastructure supporting innovative missions

Space operations recently have changed significantly, with Falcon 9 and Falcon Heavy rockets landing on ocean platforms and some being recovered and reused. 164 total spaceflight launches are projected for 2018, up from 84 in 2017 and the first year since 1990 that there will be more than 100. (Wikipedia, Timeline of spaceflight) The record for commercial launches only shows a similar pattern. 107 commercial launches are projected for 2018, up from 53 in 2017. (Wikipedia, Space launch market competition) The recent launches have been mostly similar to those in the past and included commercial satellites, military and NASA systems, and space station resupply. Operations, planning and infrastructure are unchanged except for rocket recovery and reuse. The red Tesla roadster sent to Mars was a declaration that things will change.

In the medium term, if launch is cheaper, readily available, and reliable, there will be less need to have replacement satellites or space station spares on orbit long before they might be used. In the long term, logistics including inventory and supply chain will be optimized for cost and availability.

Most concepts for future space missions are well known, and current planning is mostly for familiar missions. Most launches are of integrated satellites or probes. The military anticipates that launch will cheaper, readily available, and reliable, which provides the opportunity to rapidly replace impaired space assets, such as communications, global positioning, weather, and surveillance satellites. (Air University, 2017, p. ii) For future human missions, heavy lift rockets that can avoid orbital rendezvous and staging seem preferred. In the long term, the new launch capability can be expected to inspire innovative mission concepts.

Much launch infrastructure dates to the Apollo era, but the ocean landing platforms are new. Increased launch cadence may require additional launch capacity. The success of the Falcon 9 and Falcon Heavy suggest that SpaceX's proposed BFR (Big Falcon Rocket) will meet its goals of a large payload and further cost reduction. Since the previous high launch cost made it necessary to reduce the mass and improve the reliability and performance of space systems, high launch cost led to high space system cost. With lower launch cost, space design and manufacturing should produce lower cost systems. (Wertz and Larson, 1996, p. 117) Increased production would also tend to lower cost. Innovative mission concepts will probably require innovative infrastructure to support them.

A. Microeconomic and macroeconomic impacts of improved transportation

In the microeconomics of the firm, the capital investments in production equipment and infrastructure connections are fixed in the short term. Even so, less costly, more flexible, and more reliable transportation immediately helps to reduce production costs. Material stockpiles and schedule buffers can be reduced. Product inventory and buffer production capacity can be cut. In the medium term, facilities can be changed in response to changed transportation costs. Just-in-time supply and delivery chains can be designed, possibly using warehouse hubs and product mixing distribution nodes. More transportation and more complicated transportation will be used to achieve an overall improvement in cost and efficiency. In the long term, products may change to be come more individually tailored and supplied.

In the macroeconomics of globalization, improved transportation helps lower product cost and increase demand. It works gradually to help increase the total value of trade, the size of markets, and regional specialization. Larger more specialized markets increase innovation and productivity. Infrastructure investments in roads, railways, and airports increase the Gross Domestic Product. Trade and transport grow together. The global economy can be considered an ecosystem that is naturally seeking equilibrium and efficiency by using resources optimally for maintenance and growth. The economy evolves over the long term by implementing more effective methods in transportation, production, communications, etc.

In the transport economy, bulk freight has a low value per unit mass and is carried by truck, rail, and water. The transportation cost matters much more than speed or reliability and is a significant part of the total cost. Special cargo has high value and the transportation speed and safety of air freight can be much more important than cost.

Cheaper space transportation can be expected to lead to cheaper missions, more missions, and more transportation reliant missions. Transportation capability can be substituted for stockpiling contingency reserves, for recycling materials, and for using local resources, especially if it is less costly, more flexible, and more reliable. Cargo with much lower value per kilogram can be launched.

III. The short term impact of lower launch cost

The short term impact of lower launch cost is affected by supply and demand. There has been a recent increase in the number of launches which is expected to continue.

A. Short term supply and demand curves

A basic tool of microeconomics is the supply curve and demand curve chart shown in Figure 1.

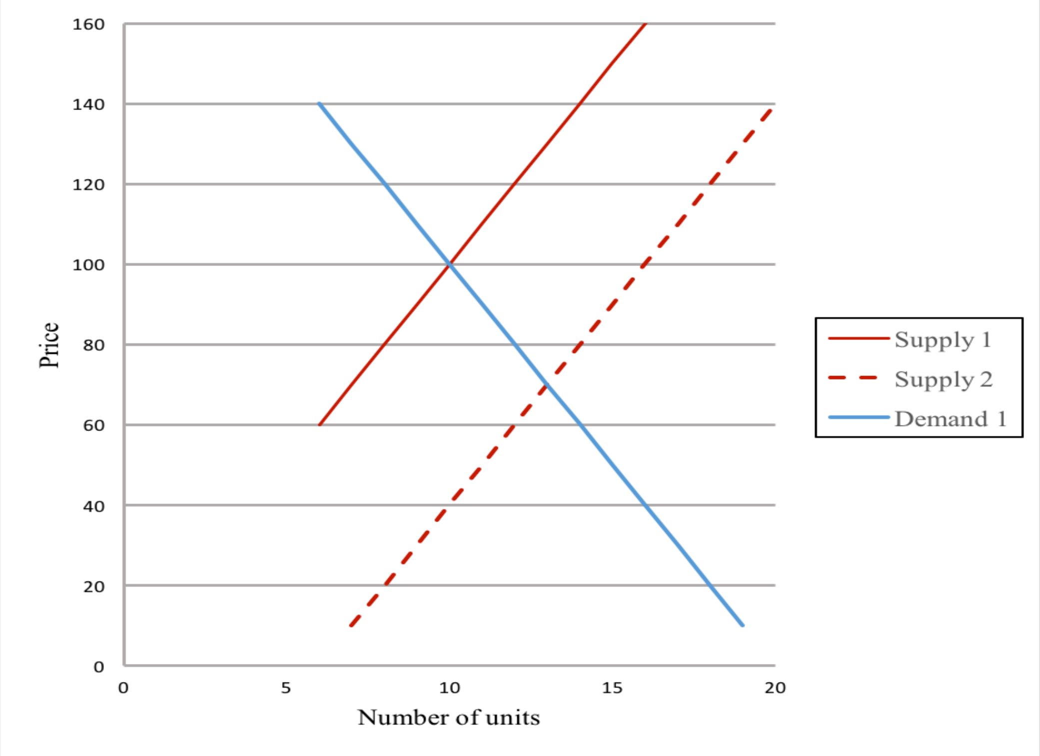

Figure 1. Supply and demand with a supply price cut.

Figure 1 is a generic illustration. The axis label values are strictly representative values, and are not meant to show the actual price, number of units, or correct shape of the supply and demand curves. The Supply 1 line slopes up as the number of units being offered increases as the price increases. The Demand l line slopes down as the number of units being taken by customers decreases as the price increases. For the original Supply 1, 10 units are sold at the market price of 100. If the asked price is decreased as in Supply 2, the supply line shifts down and right, so that more units are sold at a lower price. For Supply 2 with the original Demand 1, 13 units are sold at a price of 70.

When a price is reduced, it is usual that more units are sold. For instance, the sales of gasoline increase when the price drops and vice versa. It would be expected that the lower cost of launch to LEO would lead to more launches. The above quoted comments by Wertz and Larson on the effect of high launch cost suggest that the recent launch cost reduction by a factor of 10 or 20 should have a very large impact on the number of future launches.

Figure 1 as applied to space launch shows the recent shift of the supply curve down and to the right, from Supply 1 to Supply 2, reflecting the entry of SpaceX with significantly lower launch prices. Many more launch vehicles are now being developed, and another new entry to the market would move the supply curve further down and to the right. The supply curve is usually actually curved, sometimes with the upper part moving moving more to the right, indicating the supply increasing more rapidly at higher prices. If a new entrant can supply units only at a high price, the top of the supply curve will move right but, since the asking price is above market price, none of the new entrant's units will be sold. A new low price supplier such as SpaceX moves the bottom of the supply curve to the right and captures market share.

B. Recent and projected number of launches

Figure 2 shows the increasing number of space launches in recent years.

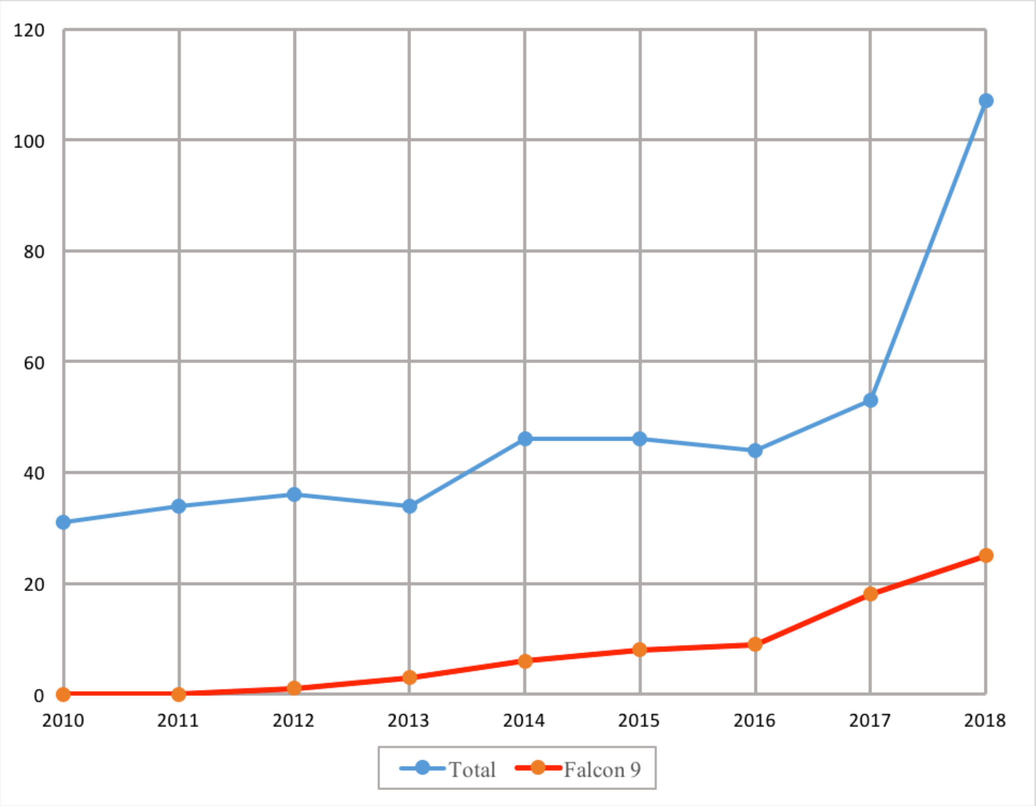

Figure 2. Increasing number of space launches. (Wikipedia, Space launch market competition)

107 commercial launches are projected for 2018, up from 53 in 2017 and 44 in 2016. The total number of launches is expected to double for 2018. The SpaceX Falcon 9 numbers are 9 in 2016, 18 in 2017, and 25 in 2018, so the Falcon 9 accounts for the full increase in 2017 but only half the increase in the projected 2018 total. (Wikipedia, Space launch market competition)

The number of launches has increased as would be expected due to their lower cost, but doubling in a year or adding more than 50 in a year seems unsustainable. Another source projects all launches, as distinct from commercial, and projects 195 for 2018, up from 90 in 2017 and 85 in 2016, and also estimates 2019 as 86, a return to the level before 2018. However, this number includes only known space flights that "are planned in the near future," and can be expected to increase as more plans are made. (Wikipedia, Timeline of space flight) This source notes that, "The trend towards cost reduction in access to orbit is expected to continue." (Wikipedia, 2019 in spaceflight)

The number of launches so far in early 2018 confirms the expected approximate doubling of launches since 2017. There were 36 launches in 2018 up until April 14, while there were only 19 launches in 2017 before April 17." (Wikipedia, 2018 in spaceflight) (Wikipedia, 20197 in spaceflight)

Projecting the launch market is important to the space business, and media reports of a launch market forecast noted that, "The space launch services market was valued at USD 8.67 Billion in 2016 and is projected to reach USD 27.18 Billion by 2025." (ASD Reports, 2017) Assuming a roughly constant cost per launch over this decade, this would give about a three times increase in number of launches between 2016 and 2025, a compound increase rate of about 12 percent per year.

C. Short term demand

The data of Figure 2 confirms the expectation based on Figure 1 that that lower launch cost will lead to a higher number of launches. Contrary to this, it has been suggested that the number of space missions is determined by known mission needs and will be relatively unchanging. The Federal Aviation Administration (FAA) forecast of

2017 had 40 space launches in 2017, a rise to 56 in 2018, and beginning in 2019 a gradual decline to 30 per year in 2026. (Boll et al., 2017) The FAA does not predict the expected increase to 107 in 2018. The FAA appears to assume that the number of launches is unresponsive to price, which would correspond to a nearly vertical or inelastic demand curve in Figure 1.

The response of the number of launches to a reduction is launch price can be relatively inelastic because a mission has large hardware and operations costs in addition to launch cost. Launch cost is roughly 10 to 30% of total mission cost. The International Space Station (ISS) cost about $100 billion to build and operate plus another $50 billion for shuttle launch, so even if launch had zero cost, the savings would pay for only half of another ISS. (Pielke and Byerly, 2011) (Wikipedia, International Space Station)

The US 2019 military space budget is $9.3 billion - $4.8 billion (52%) for satellites, $2.4 billion (26%) for launch vehicles and $2.1 billion (22%) for maintenance and support. (Erwin, 2018) Again, if the launch budget was used to buy more satellites, only half as many more could be bought. Wertz and Larson give the cost of commercial satellites in FY00 dollars as about $120k/kg and the cost of commercial launch as about 12 $k/kg, so that in this case launch cost is only 10% of payload cost. However, small experimental satellites can cost as little as $12k/kg, equaling launch cost. (Wertz and Larson, 1999, pp. 802, 808) (Wertz and Larson, 1996, pp. 116, 254) For small experimental satellites, lower launch cost would be much more effective in increasing demand.

The launch costs per kg of payload are much higher for moon or Mars missions. The mass that must be placed in LEO includes the rockets and propulsion mass to take surface payload to moon or Mars surface and to take round trip payload to moon or Mars orbit or surface and back to Earth. A rocket's stack-to-payload mass ratio or gear ratio is the ratio, of the total of payload mass plus rocket mass plus propulsion mass that is needed in LEO to emplace the payload mass at its destination, to the payload mass. To send a system from LEO to Mars and let it be aero-captured into Mars orbit has a gear ratio of 3.6. To take a system out of Mars orbit and sent it back toward Earth and be aero-captured has a gear ratio of 3.4. Assuming that aero-capture has no propulsion cost, the gear ratio of Mars orbit round trip payload is 3.6 * 3.4 = 12.2. To descend from Mars orbit to the surface has a gear ratio of 1.3, so from LEO to Mars surface has a gear ratio of 4.7. To send a system from LEO to moon orbit and return it from moon orbit for direct reentry to Earth has a gear ratio of 4.8. To take a system from LEO to moon orbit, descend to the surface and return to orbit, and then go from moon orbit to direct reentry to Earth has a gear ratio of 16.0. (Condon et al., 2000, pp. 276-8) The launch cost of payload for the moon or Mars is 5, 10, or 15 times higher than the cost to LEO. The new lower launch cost will probably be more effective in increasing demand for launches beyond LEO, to the moon or planets, than increasing Earth satellite launches.

D. Short term supply

In the 2000's the United Launch Alliance (ULA) of Boeing and Lockheed Martin had a monopoly of US government launches, while Ariane dominated the geosynchronous Earth orbit (GEO) commercial launch market. SpaceX launched its first Falcon 9 in 2010, placed a satellite in GEO in 2012, and has performed NASA and US military launches. The competition of SpaceX has forced ULA and Ariane to cut costs and prices.

Many launch vehicles are available. The US launch vehicles in operation include Antares, Minotaur-C, and Pegasus XL by Orbital ATK, Falcon 9 and Falcon Heavy by SpaceX, and Atlas V and Delta IV by ULA. A dozen more are under development in the US by SpaceX, ULA, NASA, Blue Origin, Virgin Galactic, and others. (Kim, 2017) (Wikipedia, Space launch market competition) Prominent current foreign launch vehicles include Ariane 5, Vega, Proton, Soyuz-2, Long March, Zenit-3F. (Wikipedia, Timeline of spaceflight) (Wikipedia, Space launch market competition) (Wertz and Larson, 1999, p. 802) (Wertz and Larson, 1996, p. 116)

IV. The medium term impact of lower launch cost

The short term impact of lower launch cost seems to be an increase in the number of missions, but the missions seem to be similar to past ones, based on the same concepts and largely using the same fixed infrastructure. In the medium term it can be expected that missions and infrastructure will change in response to lower launch costs.

A. Medium term supply

Figure 1 showed the original shift of the supply curve down and to the right, from Supply 1 to Supply 2, reflecting the entry of SpaceX with significantly lower launch prices. The tendency for the full supply curve to shift down and right is expected to continue. Kim notes that there was one US launch company, ULA, in 2006, three more now, SpaceX, Orbital ATK, and Blue Origin, and possibly a dozen total by 2020. He sees a "Potential Speculative Bubble in the U.S. Commercial Space Launch Industry." "Based on macroeconomics law of supply and demand, a sudden increase in the supply of launch vehicles without the suitable demand can be detrimental to the industry. If the industry is not able to achieve a sustainable growth and become a stable market operating under healthy competition, it is likely to run in to a contraction." (Kim, 2017, p. 1)

As Kim further points out, boom and bust, speculative bubbles, are prevalent in the history of transportation. Airlines, railroads, and canals have been over developed and lost investor's capital, even while providing great economic benefits to the nation.

B. Medium term demand

Supply has increased and is expected to increase further, possibly outstripping demand. However, there is a tendency for a less expensive supply to induce greater demand, due to the factor substitution effect. Making a product or providing a service requires the use of different costly factors of production, such as land, labor, and capital in the shape of machinery, facilities, inventory, and more. If one factor becomes more expensive, producers tend to use less of it, substituting other factors to minimize the total cost of production.

"Logistics costs amount to 8.5 percent of the nation's gross domestic product (GDP), and transportation alone represents 5.4 percent of the U.S. GDP." The remainder is inventory cost including interest, warehousing, and insurance. (Goldsby et al., 2014) Transportation costs have decreased, allowing inventory costs to be reduced by using more transportation. Global supply chains have been redesigned to use widespread source networks and provide just-in-time inventory. A supply and demand chart with increased demand following increased supply is shown in Figure 3.

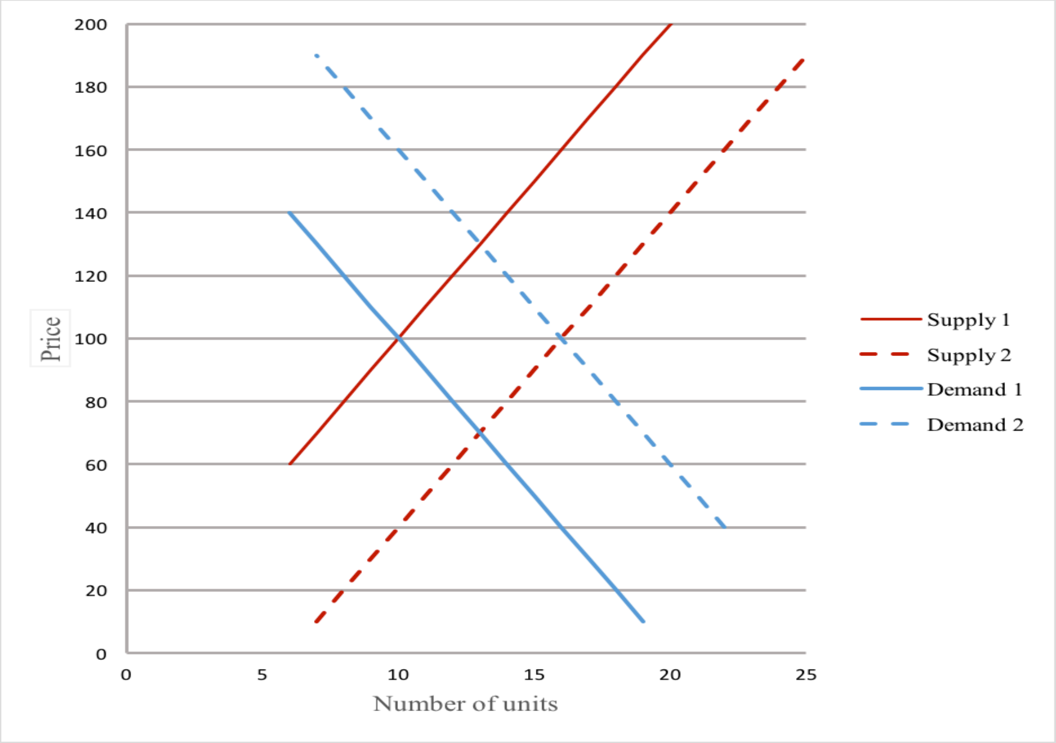

Figure 3. A supply and demand chart with increased Demand 2.

Supply 1 and Demand 1 intersected at price = 100 and units = 10. Supply 2 and Demand 1 intersected at price = 70 and units = 13. With Supply 2 and Demand 2, the number of units has increased to 16 and the price returned to the original 100.

The suggestion is that, over the medium term, a lower price supply can lead to an increased demand that is strong enough to restore the original price. This obviously would not happen in the short term. The different factors of production can be classified as fixed, such as buildings and machinery, and variable, such as contract labor and transportation. In the response to a change in a short term factor, such as a transportation cost reduction, the amount used of that factor and other short term factors can be changed. If the price reverts to the original value, the adjustments are reversed. However, in the medium term, it is possible to make capital investments to change some fixed factors to optimize production. Improved transportation networks can reduce inventory and reduce overall supply chain cost, even if the amount and cost of transportation increases.

However, in a competitive market without an established monopoly or effective discouragement of new entrants, as the space launch market appears to have recently become, the market price will reflect the actual production costs, which seem to be declining for space launch. Furthermore, in the open and highly visible space launch market, extremes of over supply and excessive demand seem unlikely.

In the medium term, similar things are done in a different way, with newly adapted infrastructure. For the ISS, less costly, high capacity, more reliable transportation would allow fewer spares to be kept on board. For ISS and future life support systems, such improved transportation would allow more direct supply of water, oxygen, and other materials and less recycling.

V. The long term impact of lower launch cost

Visionary predictions of the human future in space include innovative tourism, research, power generation, mining, manufacturing as well as the established communications, weather, positioning, and Earth imaging used commercially and by the military. All will benefit from much lower launch cost.

The long term effects of increased human use of space will be complex, reflexive, and synergistic. The human economy is now the dominant part of the closed terrestrial ecosystem with global transfers of materials and services. Significant services are now provided from LEO and especially GEO. Instead of stopping a few miles above sea level, Earth's ecosphere extends out to 22,000 miles above the equator. The purpose of the human economy is to support human life, now confined to the surface of the Earth. For the realistically foreseeable future, the demand for space launch will be to provide systems that provide scientific, commercial, and military services to Earth. If a permanent human presence is established off Earth, on the moon, Mars, or in space colonies, it will not be independent of Earth, but rather a specialized subsystem in an Earth-moon or solar ecosystem. No human group on Earth remains independent and a space settlement will be dependent on Earth for almost everything except its own specialized economic or social products.

Although some future developments can be surmised, the future trajectory of human expansion in space is unpredictable and ending in any predicted future state is unlikely. Future military demand and military supply are considered. Long term future human habitats are discussed.

A. Future military launch demand

In a time of increasing international tension, and with the expanding space capabilities of Russia and China, strong suggestions are being made that the US increase its military capability in space. President Trump has said, "My new national strategy for space recognizes that space is a war fighting domain. … we'll have a Space Force." (Cowing, 2018) Air Force Chief of Staff Gen. David Goldfein said, "I believe we're going to be fighting from space in a matter of years." (Erwin, 2018) He earlier stated that lower launch costs will help space warfighting. (Fabey, 2017)

A recent Air University white paper provides the background and rationale for a greatly increased US military presence in space.

> "(O)ur current space architecture grows increasingly vulnerable." "Fast Space envisions sortie-on-demand launch capability, made possible through economically viable business cases, high launch rates, sustainably lower costs, rapid turn-around, and higher reliability." (This provides) "The ability to immediately deliver additional effects worldwide such as precision navigation and timing, electronic warfare, cyber effects, directed energy, kinetic attack, and rapid global transport of cargo and personnel." "In short, competition in space has returned. Space is congested and contested and our advantages in space can no longer be assured. The US military depends on space assets that are increasingly at risk of attack." (Air University, 2017, pp. 1, 2, 7)

Low cost space launch provides the solution to urgent near future military problems. "(S) space is likely to become a place where the U.S., Russia, China and others decide to park weapons as technology matures and launch costs decline." (Bachman, 2018)

B. Future military launch supply

Space X has launched the Falcon Heavy and is planning the BFR, designed to take a large payload to Mars. In response to SpaceX's lower costs and increasing market share, ULA is planning to phase out its long used Atlas V and Delta IV rockets and replace them by developing the larger less expensive Vulcan. The Vulcan will have two recoverable and reusable first stage engines but not a fully recoverable rocket. It will have an Advanced Cryogenic Evolved Stage (ACES), an innovative long-lived upper stage that ULA believes will revolutionize space flight. The head of ULA says, "People don't even know what they're going to do with it yet. But I'm confident it's going to create a large economy in space that doesn't exist today." (Harwood, 2018)

Given ULA’s long history as exclusive launch provider to the US military, it’s not surprising that the Vulcan’s unique recoverable engine capability helps meet an anticipated future military demand for very high payloads. The Vulcan will launch one-third more that the Falcon 9. And, where the Falcon 9 payload must be reduced to provide propulsion to land the rocket for reuse, recovering the Vulcan engines will not reduce payload. The Vulcan first stage engine recovery requires separating a section of the first stage, reentering it behind a NASA inflatable heat shield, then when through the plasma heating region, deploying a parafoil to fly the engines to the pickup coordinates, where a helicopter will capture them. The engines account for two-thirds of the first stage cost. For large payloads, the ability to fly a larger payload than if the entire rocket was recovered more than pays for the lost remaining value of the rocket. (Harwood, 2018)

Material has been recovered from space by parachute and helicopter before, but the flexibly capable Advanced Cryogenic Evolved Stage expected in 2024 will be entirely new. The head of ULA says, “No one is working on anything like this." The ACES will have up to four hydrogen-fueled rocket engines and will be able to operate in space for weeks or months at a time. It will be able to perform complex orbital operations near Earth, the moon or beyond. This again will help meet a potential future military demand. The key to the performance of the ACES is the use of two automobile style internal combustion engines that burn oxygen and hydrogen produced by the boil-off of propellants in the main tanks. The engines will be used to pressurize the propulsion system, push propellants to attitude control jets, and generate electricity. In conventional upper stages, helium tanks are used to pressurize the propellant, hydrazine is used for attitude control, and electricity is provided by batteries. These stages are usually designed to operate only for hours, because the cryogenic propellants boil off and batteries discharge. Replacing these systems with internal combustion engines, compressors, and generators in the ACES is a major innovation creating an unanticipated and powerful new capability. (Harwood, 2018)

C. Future human habitats

Elon Musk and many others are attracted to the idea of human colonization of Mars, while some consider the moon more practical. For participation in Earth’s economic and military affairs, near Earth space from LEO out to GEO is very much more attractive. Besides being too distant for quick interaction at 1.3 light seconds, the moon is essentially a pile of useless rocks, providing a too low 1/6 Earth gravity and handicapped by its thirty-day solar cycle. The two week day and two week night create extreme heat and cold, require solar power to be augmented with a large storage capacity, and are unsuitable for Earth vegetation. Mars is far too distant for effective interaction at 3 to 22 light minutes and the typically 220 day trip time and the high cost of transportation definitively separate it from Earth’s ecosystem. A future largely independent Mars colony may be possible, but it would be of little direct economic value to Earth.

Human presence in near Earth space obviously could have military value. Important US satellite assets are vulnerable to attack and seem to require defense. Remotely controlled space defense weapons would be vulnerable to communications interruptions, and these could be countered by close human presence in orbit.

For humans to live for long periods and work effectively in space, they must be provided with much better environmental conditions than now on ISS. Zero gravity over a period of months is seriously debilitating. Carbon dioxide levels are much too high. More radiation shielding is needed to counter possible solar flares. Diet quality is impaired by the need to partially dehydrate food to save mass.

The new low cost of launch to Earth orbit allows more mass to be used to provide greatly improved human habitation and life support. Artificial Earth level gravity can be provided by a large rotating spacecraft. Technology now under development can reduce carbon dioxide levels. Added mass can provide radiation protection. Fully hydrated food and kitchen facilities can provide excellent food to support morale on difficult missions. For very long duration or permanent space habitats, water and perhaps oxygen would be recycled as now on ISS, but direct supply would be used as far as economical and if needed in case of system down time. Spacecraft rotation would provide an average temperature similar to Earth’s. Solar power would be available nearly full time. The recycling and other environmental systems would be designed to take advantage of operation in Earth gravity, with much easier design and testing than needed for the zero gravity ISS systems. Zero gravity life support can only be used for a short term human visit, so zero gravity life support is not really long duration life support. Human habitats with Earth gravity, radiation protection, solar power, and closed environmental control and life support would almost be independent space colonies. Food might be provided by some combination of artificial photosynthesis, hydroponic plant growth, and supply from Earth. Mining or manufacturing might provide an economic basis.

VI. Conclusion

Rockets capable of reaching space were first developed as missile weapons in World War II. Cold war rivalry in missile development led to the launch of the first satellite, Sputnik, in 1957. The 1960's saw the initial development of commercial and military satellites and a period of intense space activity that culminated in the Apollo moon landing in 1969. Rocket technology was relatively unchanging from the 1970's into the 2000's. The US, Soviets, Europeans, and Chinese conducted their own military launches and offered commercial launches using rockets based on missile launchers. Commercial and military satellites proliferated, numbering in the hundreds. The high value and high development cost of these satellites supported a government controlled and quasi-monopolistic rocket launch industry whose high launch costs were only a relatively small fraction of the total cost to provide satellite services.

The space industry provided irreplaceable services and was stable and profitable. Although satellite development and launch costs were quite high compared to aircraft costs, most industry participants seemed to accept this as necessary. Complaints that high launch costs were "the greatest limiting factor to expanded space exploitation and exploration" came from advocates of scientific and technical space research and development and also from believers in human space exploration and settlement. (Wertz and Larson, 1996, p. 155) Research and exploration are not directly and immediately profitable and they find it difficult to pay the high launch cost accepted by high earning satellite services. Many methods to reduce launch cost were identified, but it was obvious that "institutional barriers within government and industry have prevented major inroads in cost reduction." (Wertz and Larson, 1996, p. 155)

Elon Musk established SpaceX with the explicit intent to enable the human settlement of Mars. His engineering and business approach was to design rockets for lower cost using known methods and then to gain market share and revenue by providing lower cost commercial and later military launch. The space launch industry with its entrenched high cost methods was a classic case of a stagnant industry ripe for Silicon Valley style disruption. The initial reaction to disruptive change is often wilful blindness and denial, but the launch industry has cut costs and plans significant improvements. The US military has been unusually proactive in planning to take advantage of much lower space launch costs.

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