Economics of Launch Vehicles & Two Configurations for Tremendous Cost Reductions

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Abstract

The economics of five launch-service providers are examined and compared with operational efficiency lessons-learned data book. As a result, four economic truths are postulated and delineated. Two launch vehicle configurations are proposed that should satisfy the economic truths if properly designed. Both configurations are single-stage-to-orbit LOX/LH2 vehicles. The first launch vehicle configuration is for smaller payload capability and is air launched from a commercial air freighter while the second configuration has a larger payload capability and is a vertical-launch vehicle that stages engines as thrust requirements decrease.

Nomenclature

EMA	=	Electro-Mechanical Actuator
GEO (GTO)	=	Geosynchronous Transfer Orbit
GSO	=	Geosynchronous Stationary Orbit
Isp	=	Specific Impulse
LEO	=	Low Earth Orbit
LH2	=	Liquid Hydrogen
LOX	=	Liquid Oxygen
OEPSS	=	Operationally Efficient Propulsion System Study
GN&C	=	Guidance, Navigation, & Control
RL-10	=	Very small LOX/LH2 engine
RS-68	=	Very large LOX/LH2 engine
SSME	=	Space Shuttle Main Engine
T-0	=	Umbilicals that are disconnected at the moment of lift-off

I: Introduction

Many launch designs have been conceived since the 1950's in order to obtain routine access to space. Most have fallen short of obtaining any significant reduction in launch costs. Two particular initiatives that formulated a matrix on launch vehicle design that have built off of lessons learned are Operational Efficient Propulsion System Study (OEPSS) and Space Propulsion Synergy Team (SPST). Based upon the findings of these two initiatives, the following launch vehicle concepts are presented here within.

Launch Vehicle Market Reality

The Federal Aviation Administration's Office of Commercial Space Transportation (FAA/AST) and the Commercial Space Transportation Advisory Committee (COMSTAC) have prepared forecasts of global demand for commercial space launch services for the period 2009 to 2018. Together, the COMSTAC and FAA forecasts project an average annual demand of 26.7 commercial space launches worldwide from 2009 to 2018 for GSO and non-GSO.[i] Revenues from the 28 commercial launch events in 2008 amounted to an estimated US**$1.97 billion or $70.4M each.**[ii]

The number of launch providers has inexplicably increased in the last 5 years.[iii] The business model for these start-up businesses must be interesting. While the number of launch supply providers continuously increase, launch demand is predicted to slightly decrease. There is much publicity and excitement about space tourism increasing launch demand. Using SpaceX dragon and Falcon 9 as an example: The 17,600 lb dragon[iv] can carry seven passengers to LEO aboard the Falcon 9. The Falcon 9[v] launch service alone is $36.75M or $5.25M per passenger or $2,088 per pound. Even if the launch service cost is reduced to 10%, it would be unclear if more than 10 times as many passengers would be able to afford $525,000 just for the launch service plus the cost of riding in the dragon plus the cost of the orbital hotel.

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In the table below, only one vehicle provides launch services less than $1,500 per pound to LEO. Major changes are needed in order to reduce costs to orbit in order to increase demand.

Table #1: Cost Per Pound to LEO for various vehicles in 2007

Launch Vehicle	Country	LEO	GEO	Cost/launch	cost/lb LEO
Kosmos 3M	Russian	2,970	n/a	$12 million	$4,040
Delta-II 7420-10	USA	13,440	4,790	$50 million	$3,720
Delta-II 7925-10	USA	13,440	4,790	$50 million	$3,720
Ariane 5 ECA	European	37,950	23,127	$140 million	$3,689
Soyuz	Russian	14,758	2,975	$40 million	$2,710
Dnepr-1	Russian	8,150	n/a	$17.5 million	$2,147
Sea Launch Zenit-3SL	USA	33,541	13,440	$70 million	$2,087
Proton M	Russian	46,305	12,125	$70 million	$1,512
PSLV	India	8,140	1,760	$11 million	$1,351

Table #2 shows economic examples of five launch vehicles. Although much of the data is real, some parts are intentionally vague in order to conceal company sensitive data. The purpose of table #2 is to show that there is a fundamental economic problem with the launch service industry.

The website for Expendable #4 boasts of obtaining a 0.26% net profit over sales. In comparison, a local bakery with 1,000 employees was purchased for $2.7B in 2004; has $1.1B in sales (equal to 55% of commercial launch vehicle market) with the major material costs being flour and water. The 15-year-old product line yields a net profit at the bakery exceeding 10% of sales after paying interest on the initial investment. It may not be rocket science, but this may explain why it is so difficult to find investors and government funding in the aerospace community.

The current designs of expendable launch vehicles require extremely large, up front development costs that must be amortized over very few vehicles. At the same time, the current launch vehicle designs require hundreds of touch-laborers to prepare the vehicles for launch. The net result of these two-design flaws drive up the cost of launch services, which drives down demand in a negative feedback manner. Please bear in mind that a re-usable launch vehicle would have even more development costs with no guarantee of increase launch rate. In this paper, design options that should reduce development and operational costs thereby maximizing profit and/or increasing demand are presented.

Table #2: Economic Examples of 5 Launch Providers[vi], [vii], [viii], [ix], [x], [xi], [xii]

Item	Description	Expend 1	Expend 2	Expend 3	Expend 4	Manned-1
1	# of launches	72	9	29	36	19
2	# of years	10	6.5	10	7	10
3	Ave. launches per year	7.2	1.38	2.9	5.1	1.9
4	Development Cost ($M)	$0	$500	$585	$7,000	$5,000
5	Value of Money %	7.5%	7.5%	7.5%	4.0%	4.0%
6	$ Development / launch ($M)	$0.0	$52.3	$28.9	$165.7	$322.0
7	# of factory labor	200	100	105	0	0
8	# of touch-labor @ launch site	330	120	300	50	1,525
9	$ per man-year ($M)	$0.079	$0.079	$0.079	$0.079	$0.079
10	$ Labor / launch ($M)	$5.8	$12.6	$11.0	$0.8	$63.4
11	$ Overhead / launch ($M)	$5.8	$12.6	$11.0	$0.8	$63.4
12	$ material per vehicle ($M)	$20.0	$38.3	$20.0	$160.0	$160.0
13	Ave Launch Value ($M)	$36.7	$165.1	$85.0	$230.0	$0.0
14	Gross Annual Sales ($M)	$264.2	$228.6	$246.5	$1,182.9	$0.0
15	Gross Annual Profit (loss)	$36.5	$68.5	$40.6	-$499.9	-$1,156.8

Note: A few of the values in Table #2 are only educated guesses and this table is not meant to reveal company secrets, but merely to point out the struggles of making a profit in this industry. The manned-reusable example is presented to illustrate the double-problem of large upfront costs plus many touch labors resulting in nearly $1,200M per mission costs.

1. The Value of Money is what the Development Cost would be worth if it were invested in the stock market (minus 28% taxes paid on the net gain) instead of spent developing a rocket.
2. Development Cost per launch is equal to total development cost times value of money amortized over 10 years at the average launch rate
3. The industry average annual salary for an aerospace worker is estimated as $79,000.
4. Overhead cost per launch is conservatively assumed to be equal to touch-labor costs.
5. Material Cost is estimated by multiplying each engine by $5M (unless the engine costs are known) and adding $5M for the rest of the launch vehicle materials (unless known).

Expendable #1 has no development costs because it is a legacy launch vehicle whose development costs were expensed long ago. It is a very complicated, three stage vehicle that is built in the same factory by 600 total employees as Expendable #2. Expandable #2 was specifically designed as a low cost launch vehicle. Expendable #4 claims to make a profit of $3.5M in 2008 and for the last five years, but this is unlikely if development costs were being amortized correctly. The manned vehicle is the Orbiter Endeavor that was built without development cost for $5B and only flew 19 times in 10 years before needing a complete overhaul. The number of touch laborers was estimated by dividing the 6,100 USA workers among the four orbiters.

Economic Truths about the Launch Service Industry

Careful observation of Table #2 and strict adherence to the recommendations from the Operationally Efficient Propulsion System Study (OEPSS)[xiii] data book will reveal the following economic truths about how to obtain maximum profit in the launch service industry:

1. Minimize development costs by utilizing existing engines and infrastructure.
2. Minimize launch vehicle preparation
3. Minimize re-occurring costs by utilizing existing infrastructure.
4. Utilize LOX/LH2 propellants in order to obtain a larger useful payload to orbit; thereby, spreading the re-occurring costs around a larger customer base.

As of result of the economic truths about the launch service industry, two launch vehicle configurations are ***proposed***. The first configuration is an air-launched LOX/LH2 vehicle that can take payloads up to 15,000 lbs into LEO. Heavier payloads will require the second, more expensive (per pound) configuration, which is a vertical launch, single-stage-to-orbit vehicle that stages one or more engines.

Response to the 1st Economic Truth

Development of a new, large thrust, LOX/LH2 engine is typically estimated to be around $1B to $2B. Maximum profits will be obtained by avoiding this expense and simply designing the vehicle around existing engines. This means the air launch vehicle must be designed around the J-2X and/or RL-10 engines since the SSME is too expensive and the RS-68 engine is too large and heavy for an air-launch application. For the vertical launch vehicle, one or more RS-68 engines would qualify for the drop-away booster engines and the RS-68 and J-2X engines would make good candidates for the sustainer engine function. Table #3 illustrates that an Ares V equivalent payload can be obtained by a vehicle with five RS-68 booster engines and two RS-68 sustainer engines. Development of a booster engine recovery system could make this configuration more economical than the air launch configuration if the flight rate and re-occurring costs warrants the additional investment in the development of the recovery system and engine refurbishment.

Development and fabrication of launch pads and engine test stands is very expensive. Launching, even single stage rockets in the vertical position requires a tower and crane of some sort to erect the launch vehicle, mate the spacecraft, and provide power, cooling, propellant venting, and other connections to the launch vehicle and spacecraft. The air launch configuration eliminates this cost but at some risk; propellant must be dumped during most aborts. Air launching has another benefit during engine and vehicle development; the aircraft can be (reversibly) modified so that an engine can be mounted at the very end of the aircraft. While thrusting against propellant tanks in the cargo hold (via a long structural beam / feedline), at altitude, hot fire tests can be easily and cheaply conducted. Furthermore, by soft starting the engines, the condition of the engines can be verified before released from the launch aircraft.

NASA and the USAF should invest in the US aerospace infrastructure by requiring modifications to the RS-68, J-2X, and RL-10 engines in order to achieve wholesale reductions on the order of $1M for each engine. Such cost targets can be achieved when one compares the rocket engine turbopump to the cryogenic industry's turboexpander. The turboexpander has nearly the same loads, but costs a small fraction of a turbopump. Since the development and re-occurring costs of a turbopump (as well as hot-fire tests) are the greatest drivers to engine costs[xiv], it would not be inconceivable to achieve the above stated cost targets if production rates for the engines were maintained at a relatively high level of 20 of more engines per year. Please note that every $100M in development costs (engines, stages, or launch towers) will require a payback of more than $700K per mission if amortized over 10 years at relatively high rate of 20 missions per year.

Response to the 2nd Economic Truth

One discovery made during OEPSS was that there was very little difference in processing costs between the size of stages; therefore a two-stage vehicle should cost roughly twice as much in processing costs as a single stage vehicle.

Careful observation of Delta IV Medium Launch Vehicle Processing Timeline[xv] reveals that 25 shifts (19.5% of effort) are required for spacecraft encapsulation; 20 shifts (15.6% of effort) are required to horizontally prep and mate the first two stages; and 83 shifts (65% of effort, 7.5 weeks) are required at the pad on an 18 week processing timeline while utilizing more than 100 touch-laborers. In comparison, Ariane V requires 50 total employees (including management) to encapsulate & mate the payload to the vehicle, transport the stack to the pad, and to launch the vehicle all within two weeks![xvi], [xvii]

A properly designed launch vehicle should require no more processing and manpower than the Ariane V; **and**, according to OEPSS, a single rocket stage (be it for a vertical launch or for an air launch) should eliminate approximately half of the horizontal integration effort as depicted in the Delta IV processing timeline. In addition, a single rocket stage eliminates T-O's, swing arms, pad access platforms, and pad processing for the second or more stages.

Response to the 3rd Economic Truth

This is where an air launch configuration could have its largest economic advantage. An air launch constructed with a commercial air freighter can place the air freighter back in service during times when it is not needed for launch operations. This is in stark contrast to the Sea Launch System, which fabricated two dedicated ships that can not be utilized for any other money generating ventures between missions. NASA and the USAF should invest in the US Aerospace infrastructure by providing a shared launch pad (either stationary or ***a heavy-lift aircraft modified for air launch operations***) and other facilities to commercial ventures that would pay tolls for their use.

Response to the 4th Economic Truth

LOX/LH2 provides the highest Isp of any of the common propellants. Table #3 shows a comparison between an Atlas D and an equivalent sized LOX/LH2 vehicle. Table #3 also compares the Pegasus launch vehicle and an equivalent size LOX/LH2 air launch vehicle. The use of low Isp, expensive, solid propellants by the Pegasus launch vehicle reduced its payload capacity to only 976 lbs to LEO. The low payload capacity compounded with the low flight rate resulted in fewer opportunities to recover the development costs, which resulted in a vehicle with one of the highest cost per pound to orbit.

The findings of OEPSS state that a minimum number of propellants maximize launch operation efficiency. Therefore, adding SRB to a launch vehicle increase launch operation costs. America has handled hydrogen propellants longer than any other country. It only makes sense that we exploit this technological advantage and construct a vehicle with minimum processing costs and maximum payload.

Table #3: Comparisons between Launch Configurations

	Pegasus XL	Air Launched Centaur V-2	747 Air Launch	Atlas-D	Atlas-D LOX/LH2	Ares V Equivalent
Delta V to LEO (mph)	15,740	15,740	15,740	16,340	16,340	16,340
Gross Lift-Off Weight (lb)	52,000	50,810	240,000	255,900	255,900	3,650,000
Total Mass to LEO (lb)	1,423	9,755	45,570	8,164	41,407	574,188
Payload to LEO (lb)	976	4,745	28,975	2,990	29,300	413,800
Propellant	Solid	LOX/LH2	LOX/LH2	LOX/RP1	LOX/LH2	LOX/LH2
Engines	Orion 50SXL, Pegasus XL2, Pegasus-3	two RL10A-4-2	one J-2X	one XLR89-5 and one XLR105-5	one J-2 and one J-2	five RS-68 and two RS-68
Thrust @ Lift-Off (lb)	109,401	44,602	294,490	356,815	393,444	4,641,000
Mass of engines @ L-O	n/a	736	5,350	7,730	6,340	104,125
Mass of engines @ LEO	n/a	736	5,350	1,010	3,170	29,750
Isp, vacuum (seconds)	294	451	448	309	421	409
Mass of Tanks @ LEO	n/a	4,274	11,245	5,174	8,937	103,638
Mass Fraction	83.3%	80.8%	81.0%	95.8%	82.6%	82.2%

Assumptions: Engines will be modified to operate at the altitudes they are ignited.

An Optimized Air Launch System

Table 4 shows several large air carriers. An air launch system based upon the 747-400F is modeled due to the large numbers produced and nearing retirement. An air launch system that utilizes a 747-400F would be able to lift 248,500 lbs of vehicle and hardware to 30,000 ft at 600 mph. A used 747-400F can be obtained for less than $60M. But if not purchased outright, a 747 aircraft can be leased for only $6,000 per flight hour plus another $10,000 per hour for fuel.[xviii] If we assume an air launch would required five flight hours plus ten lease hours for a total costs of $110,000; this pales in comparison to the $30M costs for an unstacked set of SRB's on the Ariane V ($4.1M just for each SRB welded casings).[xix]. Furthermore, by purchasing the aircraft outright, a venture could customize it for air launching, transporting propellant and launch vehicle to remote launch sites (such as Diego Garcia), and for conducting hot fire tests. As a purchased asset, the 747 cargo carrier would still be available most of the month for lease to air transportation customers.

Table 4: Air Transporters[xx]

Aircraft	Manufacturer	Cost New ($M)	Payload Capacity (lbs)	# built	Ceiling (ft)
747-400F	Boeing	$250	248,500	697	41,000
C-5B	Lockheed	$179	270,000	108	34,000
AN-124	Antonov	$70	330,000	56	35,000
A380F	Airbus	$317	336,000	32	43,030
An-225	Antonov	?	550,000	1	36,100

The C-5B cost is in 1998 constant dollars.

An Optimized Vertical Launch System

Substantial cost reduction can be achieved by utilizing existing hardware, having only one rocket stage to orbit, EMA powered jet vanes, and by utilizing LOX/LH2 propellants. The vehicle that came close to fulfilling this design criteria was the Atlas D, which was used by the Mercury program. A modern LOX/LH2 design could utilize the J-2X as a sustainer engine and RS-68 engines as booster engines that are staged. Major cost reductions could be obtained if the RS-68 engines are recovered and re-used.

Final Considerations

A non-chemical, in-orbit transportation system is needed. The payload capacity of a launch vehicle to place a payload into GTO is only 52% to 57% of the same launch vehicle capacity to LEO. Going from GTO to GSO further reduces a launch vehicle capacity by 76%. Therefore, a space tug that could autonomously rendezvous with a payload in LEO and transport the payload to the ISS or to GSO could instantly increase the payload capacity of a launch vehicle by 2.5 times. In addition, the guidance system of the launch vehicle would not need to be as refined. Typically, three GN&C (Guidance, Navigation, & Control) systems are utilized to place a payload into its precise orbit. As such, the price of the GN&C systems vary with precision from $250K to $2.5M. Since the space tug would be performing the duty of rendezvous, only it would need the higher precision GN&C systems while the launch vehicles would only need the less expensive systems; providing a savings of approximately $7M per mission.

Candidates for the space tug include: electro-static, electro-magnetic, and electro-dynamic (E/D) tethers with plasma contactors. The tether system is preferred over the others due to its much lower power requirements. With a sufficiently large plasma contactor to complete the phantom circuit, the length of the tether can be reduced from 20 km to less than 100 meters while the output thrust can reach chemical engines levels and is only limited by the available power and current capacity of the tether. The specific impulse (Isp) of the ion thrusters are typically quoted as exceeding 2,500 seconds which is more than 5.5 times greater than a typical LOX/LH2 engine. The Isp of an E/D tether would be based upon the expulsion of mass by the plasma contactor. As such, the Isp of the E/D tether would be order of magnitude greater than that of ion propulsion while requiring less electrical power for equivalent thrust.

NASA and/or the USAF need to invest in the US aerospace infrastructure by developing a non-chemical, in-orbit transportation system. Previous attempts at designing a space tug resulted in a $750M project that went nowhere. A competitive, pay-for-performance competition that was witnessed by the Commercial Orbital Transportation System (COTS) program is needed for development of this greatly needed asset.

Conclusion

This paper compared the economic vitality of five launch systems and presented five methods of reducing launch service costs. Launch forecasts by governmental agencies predict the launch demand to remain at approximately 26.7 launches per year for the next ten years. One of the reasons why launching payloads to orbit is expensive is because the amortization of large development and infrastructure costs are spread over very few missions. Just as important are the costs associated with processing and launching the vehicles. These large costs have driven down the demand resulting in fewer opportunities to recover the development costs.

Two launch configurations were presented that should fulfill the requirements of a launch vehicle that can obtain an order of magnitude reduction in cost per pound into orbit. The vehicle configurations are designed so that performance is sacrificed in order to obtain lower processing and lower development costs. Solid rocket motors are usually promoted into launch vehicle designs as being reusable and cheap. However, the booster portion of an air-launched system (the aircraft) is infinitely more reusable and orders of magnitude less expensive to operate. The vertical launch system that came closest to achieving the greatest operational efficiency was the Atlas D, which was used to launch manned Mercury space capsules into LEO. Increases in operational efficiency usually result in lower payload capacity to orbit; greater payload capacity can be obtained by the use of LOX/LH2 for which the USA has the greatest operational experience. Comparisons were made between a turbopump and an equivalent size and function turbo-expander that costs orders of magnitude less.

Recommendations were made to develop a low cost propulsion system based upon turbo-expander technology as well as a development of launch infrastructure which includes a launch pad or ***a heavy-lift aircraft modified for air launch operations*** that could be utilized for fee by several different private ventures. The use of shared government infrastructure would reduce the upfront (non-reoccurring) costs companies must bear to get into the launch service business thereby reducing the price they must charge per mission to stay in business.

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