Propulsion Economic Considerations for Next Generation Space Launch

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This paper describes the major costs associated with new space launch vehicles, and analyzes how they are affected by propulsion and other design choices. These costs are broken down into hardware, operations, risk, development, and propellant categories. The amortized cost of development at likely near term launch rates, and the cost of risk (especially for manned systems) seems to favor evolutionary and multi-stage rather than revolutionary and single stage designs. Examples are given of how cost optimized and performance optimized launch concepts differ. Lastly, potential developments that could drastically alter the conclusions of the above analysis are discussed.

Nomenclature

a = amortization factor
c_H = cost of vehicle hardware per unit weight
c_L = cost of labor per man-hour, including overhead
c_P = cost of propellant per unit weight
c_{PL} = cost of payload per unit weight
c_T = specific launch cost = C_{TOT}/M_{PL}
c_1 = specific launch cost of stage 1
c_2 = specific launch cost of stage 2
C_{TOT} = total launch cost
f = fraction of launch vehicle expended in one mission
j_1 = stage 1 payload to vehicle payload ratio = $(M_{PL}+M_{S2}+M_{P2})/M_{PL}$
L = labor intensity
M_P = vehicle propellant mass
M_{PL} = vehicle payload mass
M_S = vehicle structure mass
M_{P2} = stage 2 propellant mass
M_{S2} = stage 2 structure mass
P_{FAIL} = probability of a mission failure
q = propellant-structure mass ratio = M_P/M_S
r = structure-payload mass ratio = M_S/M_{PL}
r_1 = stage 1 structure-payload mass ratio (stage 1 payload includes both upper stage and vehicle payload)
r_2 = stage 2 structure-payload mass ratio
η = propellant mass fraction = $M_P/(M_P+M_S)$
λ = structure cost = C_{TOT}/M_S
λ_1 = stage 1 structure cost
λ_2 = stage 2 structure cost
λ_H = vehicle hardware structure cost
λ_K = risk structure cost
λ_L = flight operations structure cost
λ_P = propellant structure cost
λ_R = recurring structure cost
λ_{NR} = non-recurring structure cost

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I. Introduction

Space launch vehicle economics is a subject of considerable interest and study to businesses in the space launch industry. Space launch cost calculations done by these businesses are usually not published, however, because they contain trade secrets. The reluctance of space launch economics experts to publish their cost information leaves many aerospace engineers with a poor understanding of how their work affects the cost of space access. This paper describes a simple but useful cost model for space launch vehicles and a "back of the envelope" estimate of current space launch costs. This information is then used to determine the likely characteristics of economical next generation launch vehicles. The cost model can also be combined with rocket performance models, allowing researchers to determine the approximate specific launch cost and minimum cost configuration for a given launch vehicle concept.

II. Cost Model

The cost model used in this analysis is based on the equation:

$$c_T = r\lambda \tag{1}$$

where

c_T = specific launch cost = total launch cost / payload mass
r = structure-payload mass ratio = structural mass / payload mass
λ = structure cost = total launch cost / structural mass.

This cost model is similar to previously published models, such as those by Griffin[1], Claybaugh[2], Kalitventzeff[3], and Carton[4]. It has the benefit of dividing the problem of launch cost into two variables, r and λ, that reflect different areas of study. The value of the variable r is driven primarily by technology and the physics of the orbit desired. The calculation of r is beyond the scope of this paper, but it can be determined from historical trends, simple rocket equation analysis, or detailed engineering studies depending on the level of accuracy desired. Sample values of r for several current launch vehicles are shown in Table 1. The value of the variable λ is driven by economics and program management. Determining the value of λ will be discussed in greater detail below.

Table 1. Values of *r*

Vehicle	*r* (to LEO)
Atlas V 400	2
Proton M	2.2
Ariane 5	5.2
Space Shuttle	12

Structure cost, λ, can be expressed as:

$$\lambda = \lambda_R + (\lambda_{NR} / a) \tag{2}$$

where λ_R is the recurring launch cost per unit of vehicle structure, λ_{NR} is the non-recurring cost of the launch system per unit of vehicle structure, and a is an amortization factor that determines how much of the non-recurring system costs are charged to each launch. The amortization factor a is typically proportional to the launch vehicle flight rate.

Recurring structure costs can be further broken down into the categories of vehicle hardware cost, operations cost, risk cost, and propellant cost.

$$\lambda_R = \lambda_H + \lambda_L + \lambda_K + \lambda_P \tag{3}$$

Vehicle hardware cost per unit of structure mass is[2] the product of the fraction of the vehicle expended in a launch, f, and the cost of vehicle hardware, c_H.

$$\lambda_H = f c_H \tag{4}$$

For a fully expendable launch system f would have a value of 1. For a reusable system f would represent the fraction of the vehicle that is worn out during each mission. Some researchers[3,4,5] prefer to separate the hardware cost into more detailed categories such as "engine" and "tankage" costs, but that additional level of detail is not required for the analysis in this paper.

Operations cost per unit of structure mass is[2] the product of the cost of labor including overhead, c_L, and a labor intensity parameter, L.

$$\lambda_L = Lc_L \tag{5}$$

For expendable launch systems L is defined as the man-hours of launch operation labor divided by the structure mass of the vehicle. For a reusable launch system L would also need to include recovery and refurbishment labor.

It is difficult to determine the cost of risk per unit of vehicle structure because launch vehicles have many different failure modes, each with their own potential cost. For private launches the price of insurance must also be a consideration. For the simple "back of the envelope" analysis done in this paper, the cost of risk is assumed to be:

$$\lambda_K \approx P_{FAIL}\left[(c_{PL}/r) + (1-f)c_H\right] \tag{6}$$

where P_{FAIL} is the probability of a mission failure resulting in vehicle and payload loss, and c_{PL} is the value per unit mass of the payload. This equation will likely produce a low estimate of the risk cost because it only estimates the direct cost of the lost vehicle and payload. A real mission failure would also incur indirect costs resulting from schedule delays, public relations problems, accident investigation, and similar factors..

The cost of propellant per unit of structure mass is a product of the propellant-structure mass ratio, q, and the cost per unit mass of the propellants, c_P.

$$\lambda_P = qc_P \tag{7}$$

where

$$q = \eta/(1-\eta) \tag{8}$$

A computer spreadsheet based on this cost model is available free on Jupiter Research and Development's website at http://www.jupiter-measurement.com/research/rocketcost.xls.

III. Current State of Launch Costs

Table 2 lists values typical of the economic characteristics for current generation space launch vehicles. The range of values for c_H is from Worden[6], the range of values for L is from Claybaugh[2] and Griffin[7], and the range of P_{FAIL} is from information presented by Chang[8]. The value for c_P assumes a liquid fuel vehicle. Rocket propellant prices are available from the Defense Energy Support Center, and are provided online at http://www.desc.dla.mil/DCM/DCMPage.asp?LinkID=DESCCutomerService under the heading "missile fuels." The range of values for λ_{NR} assumes that non-recurring costs are limited to vehicle R&D costs, and is from Claybaugh[2] supplemented by information given by Isakowitz[9] and at the website http://www.astronautix.com. In order for the data in Table 2 to be useful in calculating the current state of launch costs, the amortization factor, a, and values for the launch vehicle parameters r and η must also be known. For this analysis a will be assumed to be 27. This value for a is based on a 10 year payback of the non-recurring costs with a 4 year development program followed by 27 flights over the next 6 years, a flight rate typical of current American space launch vehicles[8], and neglecting interest or inflation. Wertz[10] presents a description of the effect of interest and inflation on launch costs that may be useful to researchers wanting a more detailed treatment of amortization. The value of structure-payload mass ratio, r, used for estimating current

Table 2. Current Generation Launch Vehicle Economic Characteristics

Characteristic	Values
f	1
c_H	\$1100/lb.to \$2300/lb.
L	1 to 20
c_L	\$100/hr
P_{FAIL}	2% to 5%
c_{PL}	\$10,000/lb.
c_P	\$0.1/lb. to \$0.25/lb.
λ_{NR}	\$20,000/lb.to \$120,000/lb.

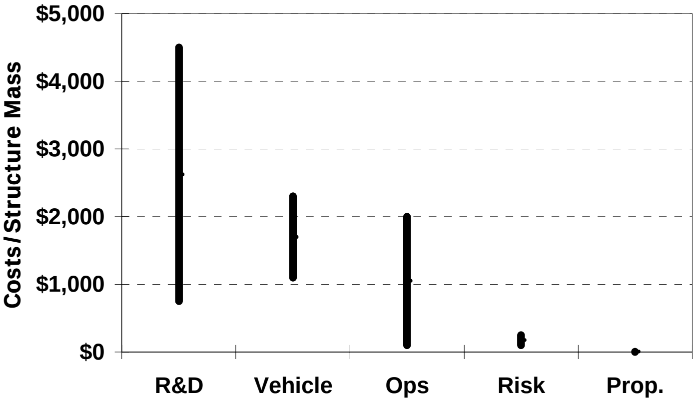
launch costs will be 2, and η will be assumed equal to 0.9. These values are not conservative, in order to represent the best case for current space launch costs.

Table 3 gives the estimated current state of launch vehicle costs from this cost model using the above information and assumptions. This estimated cost information is also presented graphically in Fig. 1.

Table 3. Estimate of Current Space Launch Structure Costs to LEO

Cost	Value
Non-Recurring, λ_{NR}	\$750/lb. to \$4,500/lb.
Vehicle Hardware, λ_H	\$1,100/ lb. to \$2,300 lb.
Operations, λ_L	\$100/lb. to \$2,000/lb.
Risk, λ_K	\$100/lb. to \$250/lb.
Propellant, λ_P	\$1/lb to \$2.5/lb.

Figure 1. Estimate of Current Space Launch Structure Costs to LEO



The costs given in Table 3 and Fig. 1 are in dollars per pound of vehicle structure mass. To convert this to launch cost per pound of payload mass you must multiply these costs by the value of r, which in this example is 2. The resulting estimate of current space launch costs to low earth orbit (LEO) suggests that the two largest components of space launch cost are the amortized non-recurring cost, which in this analysis is limited to R&D costs, and the cost of vehicle hardware. This conclusion contradicts the "conventional wisdom" that the two biggest components of space launch cost are vehicle hardware and flight operations. Flight operation costs may not even be the third biggest contributor to space launch costs with the current generation of launch technology. Using the best current practices the cost of operations and the cost of risk were both estimated at approximately \$100/lb. As discussed above, however, the cost model used probably produces a low estimate of the cost of risk because it only includes direct costs. Once indirect costs, such as accident investigations and schedule delays, are considered the third largest contributor to cargo space launch costs would likely be the cost of risk, with the cost of operations close behind as the fourth largest cost component. For manned launches, where the cost of failure is much higher than for cargo, the cost of risk would certainly overshadow the current state of operations costs. The cost of propellant is insignificant and can be ignored in a "back of the envelope" analysis.

IV. Reducing Next Generation Launch Costs

A. Amortized Non-Recurring Costs

Even if all other cost components could be eliminated, the current amortized non-recurring costs would still keep space launch costs above \$1000/lb of payload to LEO. If truly cheap space access is desired, then some way must be found to reduce the amortized non-recurring costs of the next generation of launch systems.

One important step in reducing amortized non-recurring space launch costs is to make that goal a design consideration from the very beginning of the launch system development project. Space launch vehicle concepts that are designed with low development costs in mind look different from performance optimized concepts, or even concepts designed for just minimum recurring costs. A good example of how considering amortized non-recurring costs can affect a launch

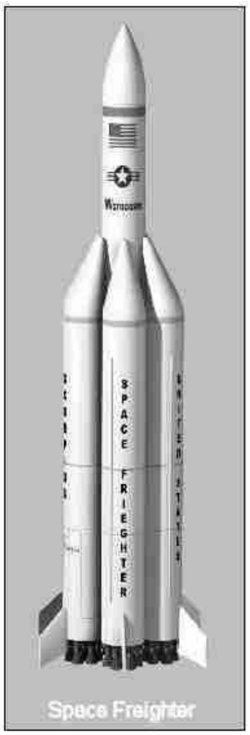


Fig. 2. Microcosm's Space Freighter Concept

vehicle design is Microcosm's Scorpius Space Freighter[11] concept shown in Fig. 2. Rather than use a few large rocket engines to propel the Space Freighter, Microcosm chose to use a large number of small (20,000lb. thrust) engines. Because a small engine is cheaper to develop, the R&D cost of the vehicle is much lower and the vehicle economics are improved over a similar vehicle with more conventionally sized engines. This arrangement has disadvantages from a purely performance standpoint, but the increase in structure-payload mass fraction from those performance losses are more than compensated by the reduced structure cost achieved through minimizing development effort. The Scorpius Space Freighter vehicle in Fig. 2 also illustrates similar economic optimization at the expense of performance in the use of identical clustered propellant tanks.

Another way to reduce amortized non-recurring costs is to eliminate development costs by using off-the-shelf components. To illustrate the cost benefit of using off-the-shelf components, consider the example of developing a new engine versus purchasing an existing engine for the sample current generation launch vehicle. Assuming that the sample launch vehicle achieved the lowest costs in each category of Table 3, it would have a structure cost of approximately $2,050/lb. These sample costs were calculated assuming a structure-payload mass ratio of 2 and η of 0.9. This performance could be achieved with a two stage rocket having a stage 1 engine I_{SP} of 331 s and a stage 2 engine I_{SP} of 462 s. Figure 3 shows the result of a simple trade study to develop a new engine design with a higher I_{SP} to replace the existing stage 1 engines. This analysis assumes that the mass and the cost of the new engine are identical to the existing engine. The solid line in Fig. 3 shows the increase in non-recurring cost that can be justified vs. the resulting improvement in I_{SP} of the new engine. The dashed line in Fig. 3 shows the size of the engine that can be developed with the increased non-recurring cost assuming a vehicle structure mass with the original engine of 100,000 lbs. and basing engine development cost on the Spacecraft/Vehicle Level Cost Model from the NASA Johnson Space Center website at http://www.jsc.nasa.gov/bu2/SVLCM.html. Since rocket engines for launch vehicles of this size frequently weigh over a ton, it can be seen from Fig. 3 that a new engine development program must promise tens of seconds of additional specific impulse in order to economically justify its cost. At the present state of engine technology, off-the-shelf engines will frequently be the most cost effective choice.

Even when off-the-shelf components cannot be used, savings can still be made by using off-the-shelf technology through evolutionary, rather than revolutionary, design. All of the launch vehicles proposed for the Evolved Expendable Launch Vehicle program illustrate this strategy. Another advantage of using an evolutionary development path for launch vehicles is the reduction of risk. As explained above, the cost of the risk of a launch failure is probably the third largest contributor to cargo space launch costs. Using evolutionary designs minimizes the development unknowns that could result in a launch failure.

When large technology development efforts are conducted, the space launch system's non-recurring costs can still be kept low if some or all of those R&D costs are paid for by other applications of the technology. Sharing the development cost of new technologies with non-space launch applications is the most likely way for a large technology development program benefiting space launch vehicles to be justified economically. This means that technologies, such as rocket-based-combined-cycle engines, scramjet engines, or materials developments which have many potential applications are easier to justify economically than technologies, such as skyhook tethers, which may provide greater space launch benefits for less effort but have few other potential applications.

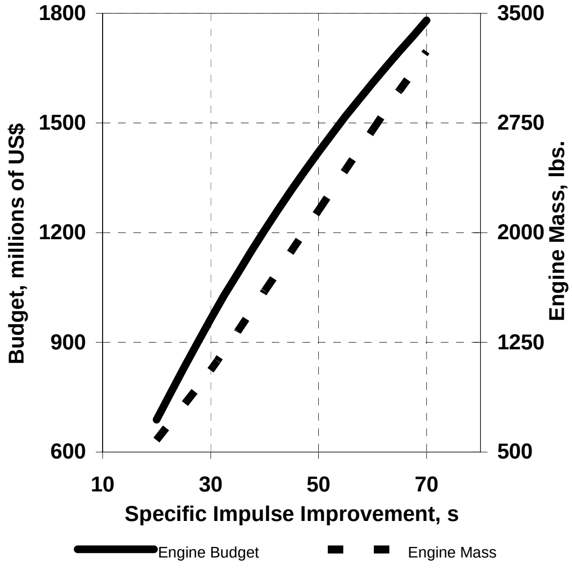


Figure 3. Economically Justified Rocket Engine Development Budget and Engine Size vs. I_{SP} Improvement Produced

An alternative strategy to reducing the amortized non-recurring launch costs is to increase the amortization factor. This usually requires increasing the launch vehicle's flight rate so that the non-recurring costs are spread over a larger number of launches. Ways of dramatically increasing a launch vehicle's flight rate include: using on-orbit assembly to launch large payloads with multiple flights[12], using clustered identical vehicles to launch large payloads with one multi-vehicle flight, or spreading out into new markets that provide additional launch opportunities beyond the current space launch industry[13]. The construction of the International Space Station is an obvious example of on-orbit assembly. Bimese[14] and trimese[15] rocket designs are examples of cluster vehicle concepts. Unfortunately cluster vehicles usually require very non-optimal staging that increases the structure-payload mass ratio enough to overcome the benefit of reduced amortized non-recurring costs. Whether launching a cluster of identical vehicles should be modeled as an increase in the amortization factor (because you are flying more than one vehicle per launch) or as a decrease in non-recurring costs (where the cluster is considered to be one larger vehicle whose development is made cheaper by copying stages) is debatable, but for this analysis it is modeled as an increase in a. Potential new markets for space launch vehicles would include space tourism[13], suborbital weapons delivery[16], fast suborbital cargo delivery[14], and fast suborbital passenger delivery[17]. Most of these applications do not require orbital flight, and provide a potential evolutionary development path where a suborbital vehicle could be incrementally improved into an orbital vehicle. As discussed earlier, evolutionary vehicle development could be used to reduce both development cost and risk cost.

B. Vehicle Hardware Costs

Lowering vehicle hardware costs has been considered an important part of making space launch more economical since the beginning of the space age. As shown in Eq. 4, vehicle hardware cost per unit of structural mass is a product of two parameters: the fraction of the vehicle expended, f, and the cost of the vehicle hardware, c_H. There are two popular schools of thought on improving vehicle hardware economics, each focusing on a separate parameter. Reusable vehicles attempt to lower λ_H by reducing the amount of the vehicle that is expended in each flight. The expendable big-dumb-booster approach[18] attempts to lower λ_H by reducing the cost of vehicle hardware. There are, of course, hybrid concepts that include some component of each approach. Both approaches typically improve structure cost at the expense of additional weight, increasing the vehicle's structure-payload mass ratio. The optimum amount of either reusability or "dumbness" for a given launch concept can be determined by combining the cost model with the vehicle performance model so that the minimum cost condition can be calculated. Whitehead[5] suggests plotting iso-cost graphs with structure cost on one axis and vehicle mass ratios on the other to help visualize the effect of trading cost and weight against each other.

Analysis from Wertz[10] argues persuasively that reusable space launch vehicles are still not economically competitive with expendable ones. One of the major reasons for this conclusion is that the vehicle hardware savings promised by reusable systems are offset by not just additional weight, but also by higher amortized development costs. Based on this analysis it appears that the next generation of economical cargo launch vehicles will likely be expendable systems. For reusable launch systems to be economically justified, something must occur to reduce the amortized non-recurring costs. This could be a much higher launch rate than currently projected or a technological development that provides a large improvement to reusable launch vehicle performance but is paid for, at least partially, by non-space launch applications. An evolutionary vehicle development path, particularly if combined with a lean organization, might be another way that the amortized non-recurring cost could be reduced enough to make reusability an economically viable choice for launch vehicle concepts. This evolutionary path might lead to the next generation launch vehicles initially flying as expendable vehicles with reusability added later in the design's life.

Staging has a noticeable effect on the economics of vehicle design, with different stages on the same vehicle having different minimum cost configurations. This can be illustrated with the example of a two stage space launch vehicle where the costs of the stages are considered separately. The total vehicle cost is the sum of both stage costs.

$$c_T = c_1 + c_2 \tag{9}$$

This can be rewritten as:

$$c_T = j_1 r_1 \lambda_1 + r_2 \lambda_2 \tag{10}$$

where

j_1 = the stage 1 lifted mass to vehicle payload mass ratio = (stage 2 mass + payload mass) / payload mass.

The parameter j_1 appears in the first term of Eq. 10 because c_T is in dollars per unit of vehicle payload but the variable r_1 is the ratio of the first stage's structure to the first stage's payload. Since the payload of the second stage is also the same as the vehicle's payload, no similar parameter is needed in the second term. Researchers preferring consistency may want to add a j_2 parameter to the second term of Eq. 10, and then set j_2 equal to 1. Assuming that all the stage mass can be divided into structure and propellant allows the definition of j_1 to be rewritten into a more useful form.

$$j_1 = (M_{PL} + M_{S2} + M_{P2}) / M_{PL} = 1 + r_2 + r_2 q_2 \tag{11}$$

Combining Eq. 10 with Eq. 11 gives the vehicle structure cost as a function of the stage structure costs and the stage structure-payload mass ratios.

$$c_T = r_1\lambda_1 + r_2 r_1 \lambda_1 + r_2 q_2 r_1 \lambda_1 + r_2 \lambda_2 \tag{12}$$

The effect of stage location on economic decisions becomes obvious from examining Eq. 12. The variables r_1 and r_2 appear in the same number of terms, so that if λ_1 and λ_2 have approximately the same value then a percentage change of either r_1 or r_2 will have the same effect on the vehicle's specific launch cost. The variable λ_1 appears in three of the terms but λ_2 appears in only one term, so for typical cases a percent change to λ_1 will have a larger effect on the vehicle's specific launch cost than a similar change to λ_2. This can be understood by considering the normal configuration of a two stage rocket, with a large first stage topped by a much smaller second stage. If the first stage is ten times larger than the second, then a dollar per pound reduction in the first stage's structural cost will have ten times the effect on the vehicle's specific cost than a similar dollar per pound reduction in the second stage's structural cost. These relationships between r_1 and r_2 and between λ_1 and λ_2 in Eq. 12 mean that technologies used to reduce stage structural cost at the expense of increased structure-payload mass ratio should be put in the first stage because they will produce more savings at the same weight penalty. Technologies that reduce the stage's structure-payload mass ratio, but increase stage structural cost should be used in the second stage to get the performance increase for the least possible cost. A similar effect occurs on rockets three or more stages. These trends will drive economical launch vehicles to have relatively high performance, high cost upper stages on relatively cheap, but heavy lower stages.

The idea that weight savings on the upper stages of a multi-stage rocket is more valuable than weight savings on the lower stages is hardly a new discovery; rockets have been built that way since staging was developed. What Eq. 12 does do, is to illustrate this effect of a stage's position in a rocket on its minimum specific cost configuration. Because the goal of adding reusability to a stage is to decrease its structural cost, usually at the expense of increasing the stage's structure-payload mass ratio, Eq. 12 also demonstrates that economical cargo launch vehicles should develop reusable lower stages before they develop reusable upper stages. Having an expendable upper stage on a reusable lower stage seems to contradict the usual trend of reusable vehicle concepts. From the Reuse Crew Module[19] design for Apollo, through the Space Shuttle, to current Crew Exploration Vehicle designs, high profile reusable space vehicle concepts typically have a reusable upper stage on expendable lower stages. These high profile reusable concepts are intended to be manned vehicles, not economical cargo launch vehicles. Because a manned system requires you to recover the upper stage anyway, in order to recover the crew, there is less penalty to adding reusability to the uppermost stage of a manned system. The original Boeing EELV concept with a partially reusable first stage (described at http://www.fas.org/spp/military/program/launch/eelv_b.htm) is an example of an economical cargo launch vehicle concept incorporating reusability on a lower stage, while using an evolutionary vehicle development path to reduce non-recurring costs.

V. Conclusions

Despite the roughness of the cost assumptions used, the cost model described in this paper allows several conclusions to be drawn about economical next generation space launch vehicles. To achieve low cost access to space, methods of reducing the high amortized non-recurring costs of space launch vehicles must be found. Economical next generation space launch vehicles will make high use of off-the-shelf components and evolutionary technological development to reduce non-recurring costs. Major new developments in economical space launch technology will be partially or fully paid for by non-space launch applications, such as aircraft or weapon system applications, to reduce non-recurring costs.

The cost of vehicle hardware must also be reduced to provide low cost space launch capability. Economical next generation cargo launchers will likely have a high performance expendable upper stage on a relatively cheap expendable lower stage. The expendable lower stage may evolve into an even lower cost reusable stage if flight rate and technological development permit. Also, suborbital reusable vehicles developed to take advantage of high launch rates in new space markets may economically evolve orbital capability by adding a high performance expendable upper stage. For the next generation manned launcher, the need to have a recoverable upper stage for the crew will continue to make reusable upper stages economically attractive.

Lastly, an economical launch vehicle does not resemble a performance driven space launch vehicle in configuration, component sizing, or mission design; to be successful an economical launch vehicle must be designed for minimum specific launch cost from the beginning of the project. Economic performance is not something that can be added as an afterthought.

The cost model described in this paper should be of interest to researchers wanting to study the cost of space access or the design of minimum cost launch vehicles. Care should be taken, however, in using this model or the analysis presented here to predict future events in launch vehicle development. In the real world, economics is not the only driver of launch vehicle design. Public launch vehicles may be developed for non-economic reasons, such as national security or political goals. A profitable launch vehicle for a private company may not necessarily be an economical launch vehicle. For example, if a private launch company can get government funding to conduct the research that they need for their own vehicle development program then they can solve the difficult amortized non-recurring cost problem and turn a profit, by pushing that cost onto a government agency, even though the vehicle may still not be economical. Future launch vehicle flight rates and vehicle development costs are notoriously difficult to predict and easy to misrepresent, so that even an organization that thinks it is funding an economical launch vehicle may discover otherwise once the vehicle goes into operation. The engineers who do succeed in developing real world economical space launch vehicles, however, will be the ones who make launch vehicle economics an obsession from the beginning.

References

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[1] Griffin, M. D., and Claybaugh, W. R., "The Cost of Access to Space," *JBIS*, Vol. 47, 1994, pp. 119-122.

[2] Claybaugh, W. R., *AIAA Professional Study Series Course: Economics of Space Transportation,* Oct. 12-13, 2002, Houston TX.

[3] Kalitventseff, B., "Various Optimization Methods for Preliminary Cost and Mass Distribution Assessment for Multistage Rocket Vehicles," *JBIS,* Vol. 20, 1965, pp. 177-183.

[4] Carton, D.S., and Kalitventzeff, B., "Effect of Engine, Tank, and Propellant Specific Cost on Single-Stage Recoverable Booster Economics," *JBIS*, Vol. 20, 1965, 183-196.

[5] Whitehead, J.C., "Launch Vehicle Cost: A Low Tech Analysis", presented at the 36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, AIAA2000-3140, Huntsville, AL, 2000.

[6] Worden, S., "Perspectives on Space Future," presented at the 2003 NIAC Fellows Meeting, Atlanta, GA Nov. 6, 2003, http://www.niac.usra.edu/files/library/fellows_mtg/nov03_mtg/pdf/Worden_Simon.pdf.

[7] Griffin, M.D., "Heavy Lift Launch for Lunar Exploration," presented at the U. of Wisconsin, Madison, WI, Nov. 9, 2001, http://fti.neep.wisc.edu/neep533/FALL2001/lecture29.pdf.

[8] Chang, I.S., "Overview of World Space Launches," *Journal of Prop. And Power*, Vol. 16, No. 5, 2000, pp. 853-866.

[9] Isakowitz, S. J., Hopkins, J., and Hopkins, J. P., *International Reference Guide to Space Launch Systems,* 4th ed., AIAA, Reston, VA, 2004.

[10] Wertz, J. R., "Economic Model of Reusable vs. Expendable Launch Vehicles," presented at the IAF Congress, Rio de Janeiro, 2000, http://www.smad.com/scorpius/IAFPaper.pdf.

[11] Chakroborty, S., Wertz, J.R., Conger, R., Kulpa, J., "The Scorpius Expendable Launch Vehicle Family and Status of the Sprite Small Launch Vehicle," presented at the 1st Responsive Space Conference, Redonodo Beach, CA, 2003, http://www.smad.com/scorpius/9005p.pdf.

[12] Wingo, D., "Transforming Spacecraft Economics Via On-Orbit Assembly," *SpaceDaily*, Jan. 30, 2002, http://www.spacedaily.com/news/satellite-tech-02a.html.

[13] Foust, J., "Is There a Business Case for RLVs?," *The Space Review*, Sept. 2, 2003, http://www.thespacereview.com/article/44/1.

[14] Olds, J. R., and Tooley, J., "The Bimese Concept: A Study of Mission and Economic Options," NASA Langley Grant NCC1-229 Final Report, Atlanta, GA, Dec. 22, 1999.

[15] Dore, F. J., "Aircraft Design and Development Experience Related to Reusable Launch Vehicles," *Reducing the Cost of Space Transportation: Proceedings of the American Astronautical Society 7th Goddard Memorial Symposium*, edited by George K. Chacko, American Astronautical Society, Washington, D.C., 1969.

[16] Daehnick, C., "Spacelift: Suborbital, Earth to Orbit, and on Orbit," Airpower Journal, Summer 1995, pp. 42-64, http://www.airpower.maxwell.af.mil/airchronicles/apj/spacast3.html.

[17] Hunter, M. W., "The Hypersonic Transport- The Technology and the Potential," presented at the AIAA 7th Annual Meeting and Technical Display, Houston, TX, 1970.

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[18] London, J. R., *LEO on the Cheap*, Air University Press, Maxwell AFB, AL, 1994, http://www.dunnspace.com/leo_on_the_cheap.htm.

[19] Raymes, F., and Dodds, J. I., "Reusable Space Transportation Systems: 1970/1980- An Evolutionary View," *Reducing the Cost of Space Transportation: Proceedings of the American Astronautical Society 7th Goddard Memorial Symposium*, edited by George K. Chacko, American Astronautical Society, Washington, D.C., 1969.