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A Critical Parameter Optimization of Launch Vehicle Costs

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Beginning in 2002, as part of the University of Maryland (UMd) Space Vehicle Technology Institute (SVTI) under the NASA Constellation University Institutes Project (CUIP), the UMd Space Systems Lab began a parametric analysis aimed at minimizing costs of payload to low earth orbit (LEO). By identifying a range of market sizes (total program payload to LEO), the effects of manipulating a number of critical parameters involving vehicle configurations on payload costs were examined. Vehicle configurations encompass single stage and multistage vehicles with combinations of airbreathing and/or rocket propulsion systems. Launch systems could be expendable or reusable on a stage-by-stage basis. Staging velocity is optimized for minimum cost at each design point. The costing model includes the effects of learning on production and operations, discount factors for multiyear investments, and the use of "refurbishment fraction" (fraction of initial procurement costs required for reusable vehicle refurbishment between flights) for estimating maintenance and turn-around costs. Overall vehicle recurring and nonrecurring costs are estimated based on sets of inert-mass cost estimating relations drawn from published sources.

Nomenclature

ACES	=	air collection and enrichment system
c_{eff}	=	effective exhaust velocity
C_{ops}	=	operations cost
C_{nr}	=	non-recurring cost
C_{refurb}	=	refurbishment cost
C_{rtot}	=	recurring cost
$C_{1st\ unit}$	=	first unit production cost
$C_{\$/kg}$	=	cost per kilogram payload
dv	=	staging velocity
δ	=	inert mass fraction
ELV	=	expendable launch vehicle
f_{refurb}	=	refurbishment fraction
g_0	=	acceleration of gravity (9.8066 m/s^2)
HTHL	=	horizontal takeoff/horizontal landing
I_{sp}	=	specific impulse
LEO	=	low Earth orbit
M_{gross}	=	vehicle gross mass
M_f	=	final vehicle mass after takeoff
M_{inert}	=	vehicle inert mass
M_{pL}	=	payload mass
M_{tot}	=	total program mass
M_0	=	initial vehicle mass before takeoff

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N_{flts}	=	number of flights in program
N_{fpv}	=	number of flights per vehicle
N_{veh}	=	number of vehicles in program
p_{exp}	=	learning curve factor
r	=	mass ratio
RLV	=	reusable launch vehicle
RBCC	=	rocket based combined cycle
SSTO	=	single stage to orbit
TBCC	=	turbine based combined cycle
TSTO	=	two stage to orbit

I. Introduction

THE Space Shuttle was originally "sold" as a means of achieving an order-of-magnitude reduction in launch costs to low earth orbit. More than a hundred flights later, no significant cost savings have been evident. During the intervening two decades, a number of reusable launch vehicle projects were initiated with the hopes of substantial cost reduction, and then abandoned in the face of enormous and escalating technical challenges and development costs. In recent years, NASA and the DOD seem to have settled on evolved expendable launch vehicles (EELVs) for operational launches, but this decision is being revisited in light of the new focus on extended human exploration of the moon and Mars. Due to these developments, it is important to re-examine the critical design choices in next-generation Earth launch systems. The goal in this study was to develop parametric models for launch vehicle performance and costing, and to apply the parameters equally to all potential systems, thus starting from a "level playing field" for the purposes of finding the most advantageous paradigms for creating a low-cost launch vehicle.

II. Mission Model and Ground Rules

The cost model developed for this analysis incorporates all of the major system and vehicle level costs associated with a fleet of new vehicles for launch to low earth orbit. Past analyses have demonstrated the critical role of total mission model in overall cost estimation[1]; for the purposes of this paper, the total launch market is assumed to be 20 million kilograms of payload delivered to LEO at an altitude of 400 kilometers over a period of 20 years. This launch rate corresponds to 40-50 flights of shuttle/EELV vehicles per year, which is a modest increase over current launch rates. The cost model includes all development costs associated with designing a next generation launch vehicle, production and facilities costs for constructing and maintaining the fleet and operations costs for launching missions.

The total program payload is divided evenly between all flights. The number of flights required is determined by the payload size, and therefore ultimately by the overall size of the vehicles. The vehicle size and number of flights required to complete the program's objectives is iterated in the model to optimize for minimum total payload costs to orbit. While an expendable launch vehicle (ELV) costs less to develop, reusable launch vehicles (RLV) might be expected to cost less on a equivalent per mission basis, as post-mission refurbishment costs for RLVs are generally lower than the equivalent production costs of more ELVs. The primary focus of this research is on evaluating competing technologies for reusable vehicles, so costing results presented will focus specifically on reusable systems unless designated specifically as an expendable vehicle or stage.

Since multiple vehicles will be constructed, learning trends will affect production costs. A constant learning curve of 80% is used for this model: that is, the 2nd unit will cost 80% of the 1st, the 4th will cost 80% of the 2nd, and so on. Sensitivity analysis is performed on several input parameters to determine the effects on the overall cost of the program. These input parameters are discussed in the methodology and results section.

The baseline vehicle examined here is a two stage to orbit (TSTO) system. It has been shown that a multistage to orbit approach has both physical and economic advantages[2] in lifting payload into orbit. Stages are modeled with rocket engines using several different types of rocket propellant and, when indicated, airbreathing engines. All dollar amounts are in $2004US unless otherwise noted.

III. Methodology

Costs are estimated using the NASA Spacecraft/Vehicle Level Costing Model[3]; this is a set of heuristic equations for various cost elements based on overall vehicle parameters, such as inert mass. To minimize the cost per kilogram of payload to orbit, it is important to determine the optimum payload size in each vehicle. A range of payload sizes is selected from 1,000 to 75,000 kilograms; this covers vehicle sizes ranging from the smallest current launch vehicles to systems with payloads three times the current largest.

For each payload size, the following data is determined. The total number of flights required over the course of the 20-year program is determined by dividing the total program payload mass by the vehicle design payload mass for each flight.

$$N_{flts} = \frac{M_{tot}}{M_{pL}} \tag{1}$$

The total number of individual vehicles required for the program is then determined by dividing the total number of flights by the number of flights per vehicle. The number of flights per vehicle is a variable that can be set, changed and optimized by the user. If an expendable vehicle is considered, then the number of flights per vehicle is set at one.

$$N_{veh} = \frac{N_{flts}}{N_{fpv}} \tag{2}$$

The mass ratio, r, is the classic measure of the rocket's design effectiveness. The mass ratio is defined as the ratio of the final mass of the vehicle after launch to the initial mass. It includes dv (staging velocity), which is the amount of velocity required for the launch vehicle to travel from the Earth's surface to circular orbit at a given altitude. The required velocity to reach a circular orbital altitude of 400 km is assumed to be 9200 meters per second, which includes standard allocations for gravity and aerodynamic losses. The staging velocity split is represented as the fraction of the total velocity (9200 m/s) at which staging occurs. For a single stage vehicle the dv split is one since all the change in velocity comes in the single stage. For a multistage vehicle the dv split for each stage is a fractional value, with all the dv split values adding up to one. The dv split between stages is optimized for each vehicle case to minimize cost. Also required to calculate the vehicle's mass ratio is the specific impulse, (I_{sp},), which is a measure of a rocket engine's efficiency and is dependent on the propellant used. Chemical propellants, which are used in the vehicles for this program, typically have a specific impulse of 200-450 seconds. I_{sp} values were set in this range with specific values depending on the type of propellant used. For the airbreathing vehicles considered in this study, the (fuel) specific impulse is set at 2000 seconds.

$$\begin{aligned} r &= e^{\frac{-dv}{c_{eff}}} = \frac{M_f}{M_0} \\ c_{eff} &= I_{sp} g_0 \end{aligned} \tag{3}$$

The inert mass fraction δ is one of the major vehicle estimating parameters, and is defined as the ratio of inert mass in the vehicle to the total mass of the vehicle. This formulation assumes that the total mass of the vehicle can be split into categories of payload mass, inert mass and propellant mass. The inert mass fractions used in this model are derived from historical data for vehicle configurations with past heritage, or are taken from detailed design studies for advanced technologies such as airbreathing stages. Typical values for δ range from 0.04 to 0.20 for vehicles with rocket engines and 0.20 to 0.40 for stages with airbreathing engines. The gross mass of each launch vehicle is calculated by dividing the payload mass by the difference of inert mass fraction from mass ratio.

$$M_{gross} = \frac{M_{pL}}{r - \delta} \tag{4}$$

The inert mass of the vehicle is determined by multiplying the inert mass fraction by the gross mass.

$$M_{inert} = M_{gross} * \delta \tag{5}$$

With the inert mass known, the costs of the launch vehicles can be determined. All the following costs are in millions of US 2004 dollars ($M2004). Inert mass is estimated using the information from the equations above. The numerical values shown are constants based on the type of vehicle, in this case a launch vehicle stage, and are determined by NASA from years of launch vehicle data[3].

$$\begin{aligned} C_{nr} &= 6.7 * M_{inert}^{\;0.55} \\ C_{1^{st}\,unit} &= 0.1 * M_{inert}^{\;0.662} \end{aligned} \tag{6}$$

The recurring, or production, costs for the vehicles are determined using the above equation, which estimates the production costs for the first vehicle built. Subsequent vehicle production costs are reduced due to learning effects, which tend to favor programs with larger production runs. The total program recurring cost is dependent on the production cost, the number of vehicles and the learning curve. The learning curve here is represented by the $p_{\exp}$ term. The learning curve for this vehicle program is set at 80%, which corresponds to a $p_{\exp}$ value of –0.32. The ideal way to account for total recurring costs would be to directly add up the estimates for each vehicle produced, which is not well suited for rapid iteration of analyses in the course of finding optimal solutions. Instead, the second equation of (7) is an approximation for total recurring costs, which is accurate to within a few percent as long as the total number of units produced is larger than ~10.

$$\begin{aligned} p_{\exp} &= \frac{\log\left(\frac{C_2}{C_1}\right)}{\log(2)} \\ C_{r_{tot}} &= C_{1^{st}\,unit} * \frac{N_{veh}^{\;(1+p_{\exp})}}{1+p_{\exp}} \end{aligned} \tag{7}$$

The vehicle refurbishment cost is dependent on the recurring cost, the refurbishment fraction, and the number of flights per vehicle. The refurbishment fraction of a vehicle f_{refurb} represents the cost required for post-flight refurbishment, expressed as a fraction of the 1st unit production cost. The refurbishment fraction's value is input by the user in this model, and based on historical data can vary from 10-20% for a launch vehicle. The X-15 program demonstrated a 3% refurbishment fraction over 199 flights, and that figure will be used as a lower practical limit for launch vehicle estimation.

$$C_{refurb} = C_{r_{tot}} * f_{refurb} * N_{fpv} \tag{8}$$

The operations cost is represented by a constant operations cost per flight, set at \$1 million per flight for this study, multiplied by the total number of flights.

$$C_{ops} = C_{op} * N_{flts} \tag{9}$$

The total cost is determined by adding the nonrecurring, recurring, refurbishment and operations costs. Note that the 1st unit production costs are not added separately here because all production costs are included in the recurring costs. The chosen figure of merit for this study is the cost per kilogram payload (\$/kg), calculated by dividing the total cost by the total program payload mass.

$$C_{\$/kg} = \frac{C_{nr} + C_{r_{NR}} + C_{refurb} + C_{ops}}{M_{tot}} \tag{10}$$

Once the database has been constructed from the equations listed above, several input variables are optimized to minimize cost. The variables, N_{fpv}, δ, M_{pL}, and f_{refurb} are user input variables in this model and can be changed. The inert mass fraction δ and refurbishment fraction f_{refurb} represent limitations of technology, and are used as independent variables in the analysis. The flights per vehicle N_{fpv} and launch vehicle payload mass M_{pL} are optimized to find values resulting in the minimal cost per kilogram of payload to orbit.

IV. Results

The results here focus on the manipulation of inert mass fraction and the relationship between refurbishment fraction and optimum number of flights per vehicle. The effects of variation of these parameters on overall program costs, recurring costs and non-recurring costs are discussed in the following sections.

A. Inert Mass Fraction

Since the SVLCM model estimates costs based on inert mass, it is intuitively obvious that as inert mass fraction increases, the payload cost to orbit rises; this trend is shown in Fig. 1.

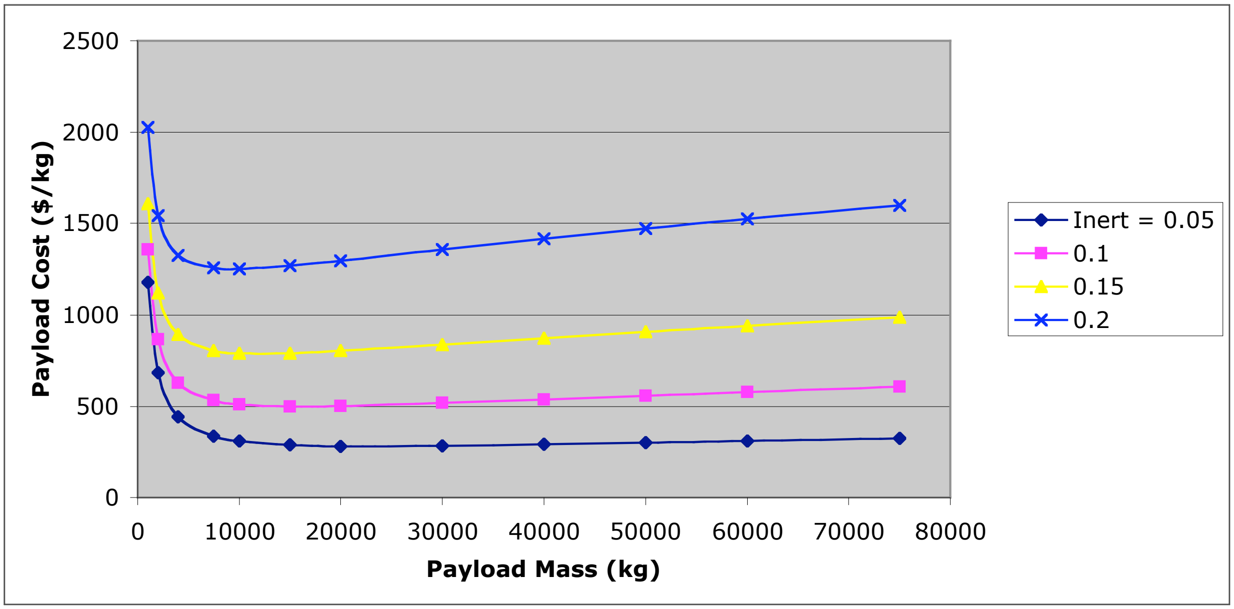

Figure 1. Inert mass fractions

It is interesting to note that, as the payload mass is varied from 0 to 75,000 kg, the payload costs always exhibit a minimum at an intermediate value of payload mass. An examination of the component costs explain the trends exhibited: at very low payload masses, the per-flight operations cost dominates due to the large number of flights. At the high end of payload mass, the vehicles are large enough that costs are dominated by nonrecurring and refurbishment costs. With fewer flights per vehicle there is less opportunity for the vehicle costs to be amortized over each flight during a vehicle's lifetime.

The specific value of optimum payload mass to minimize payload cost to orbit over the program occurs at a lower payload mass for each respective higher inert mass fraction. This is consistent with the observed trends, as higher inert mass fractions add to nonrecurring and refurbishment costs, and thus force the optimum payload size (and corresponding vehicle size) lower for minimum costs. The minimum for an inert mass fraction of 0.05 occurs closer to 20,000 kg while the minimum for an inert mass fraction of 0.20 occurs before 10,000 kg.

It is worth noting that all of these minimum cost payload sizes are subsumed within the range of current launch vehicles; in fact, even the highest inert mass fraction yields an optimum payload size less than that of the space shuttle or a heavy-lift EELV. While there may be operational considerations driving the current NASA desire for 100,000 kg payload launch vehicles for the Vision for Space Exploration, these Saturn V class launch vehicles are not likely to provide minimum launch costs.

Having demonstrated the utility of inert mass fraction as a vehicle-level estimation parameter for categorizing program costs, the next logical step is to arrive at supportable estimates for δ as a function of launch vehicle design choices, such as type of propulsion system. Historical systems, such as classical multistage rocket system, can be analyzed by the use of known databases to find estimating relations for δ. The results of this regression analysis, using historical data[4] from multiple stage vehicles including Delta, Soyuz, Saturn, Taurus, Pegasus and the Shuttle are shown in Figure 2. The historical vehicle stages were divided into four groups by propellant type (cryogenic, petroleum, solid and storable).

Multiple classical launch vehicle estimation algorithms[1,5] assume a physical economy of scale: increasing the absolute size of a stage corresponds to lower inert mass fractions, as increasing scale correlates to increasing structural efficiencies. By visual inspection, some aspects of this trend may be seen in the data of Figure 2. However, none of the data sets have mathematically acceptable regression trends, as substantial variations in δ across vehicle designs prevents an acceptable curve fit in three of the cases, and the fourth (cryogenic stages) has insufficient data points for a meaningful trend.

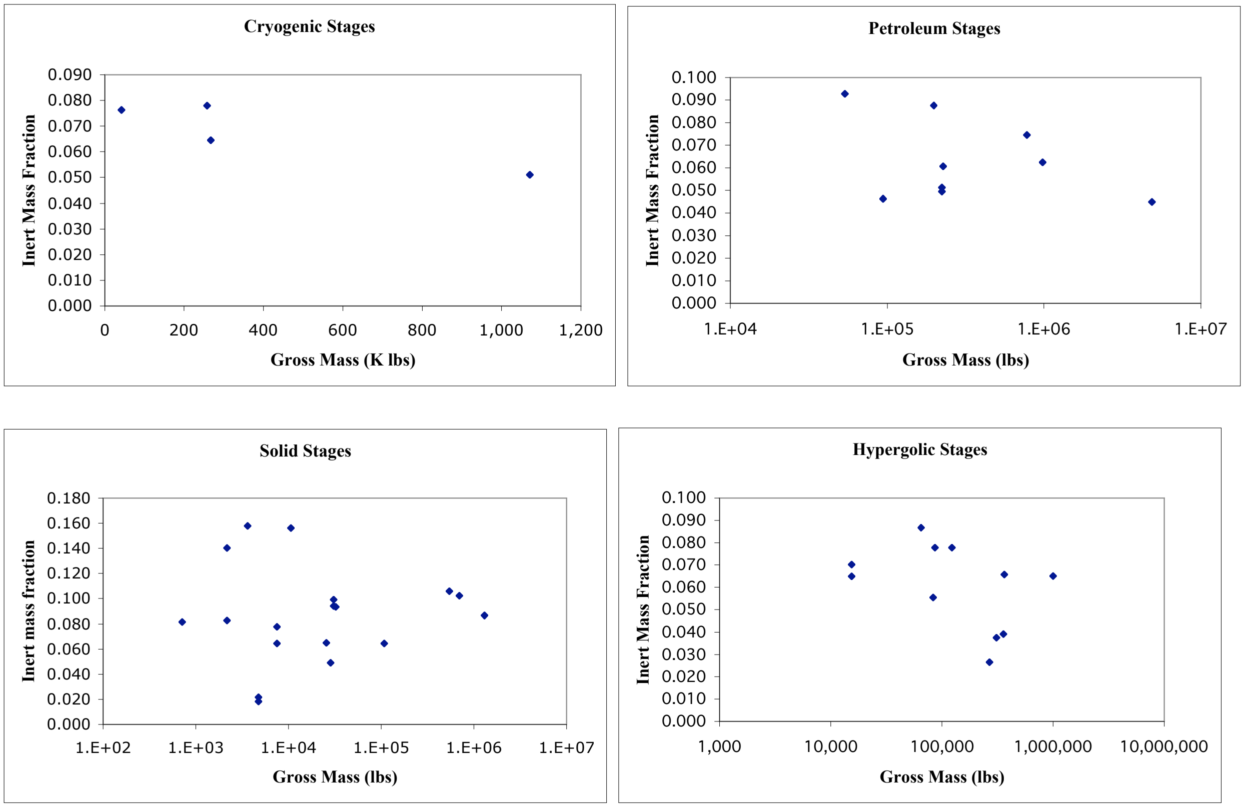

Figure 2. Gross mass vs. inert mass fraction

A second approach to inert mass fraction estimation was performed by examining vehicles, both theoretical and real, with some type of airbreathing engine. The purpose of this study was to assign an estimated range of values for inert mass fractions of stages with airbreathing engines. Those results can be found in Table 1 below, along with some rocket-based parameters taken from the regression analysis above.

Vehicle/Stage	Inert mass fraction
Space Shuttle	0.113
SSTO Rocket	0.081
SSTO Airbreather/Rocket	0.261
SSTO HTHL Airbreather/Rocket	0.261
SSTO RBCC	0.178
TSTO Airbreather/Rocket	0.379
TSTO HTHL S1-RBCC S2-Rocket	0.232 0.176
TSTO TBCC	0.379-0.425
TSTO Spaceplane Stage 1-Launcher Stage 2-Orbiter	0.318-0.414 0.127-0.173
TSTO TBCC Stage 1 Stage 2	0.371 0.198
TSTO ACES Stage 1 Stage 2	0.413 0.162

Table 1. Inert mass fractions of air breathing vehicles

Based on these figures an inert mass fraction in the area of 0.35 is a safe assumption for vehicle stages with airbreathing engines. This figure will be slightly higher for turbine based combined cycle (TBCC) engines and slightly lower for rocket based combined cycle (RBCC) engines. For this study, the fuel-specific impulse of air breathing stages is set at 2000 seconds. This is at the low end of an acceptable range of specific impulse for a jet engine (2000-3000 seconds), accounting for decreased efficiency of an airbreathing engine operating at high speeds and altitudes.

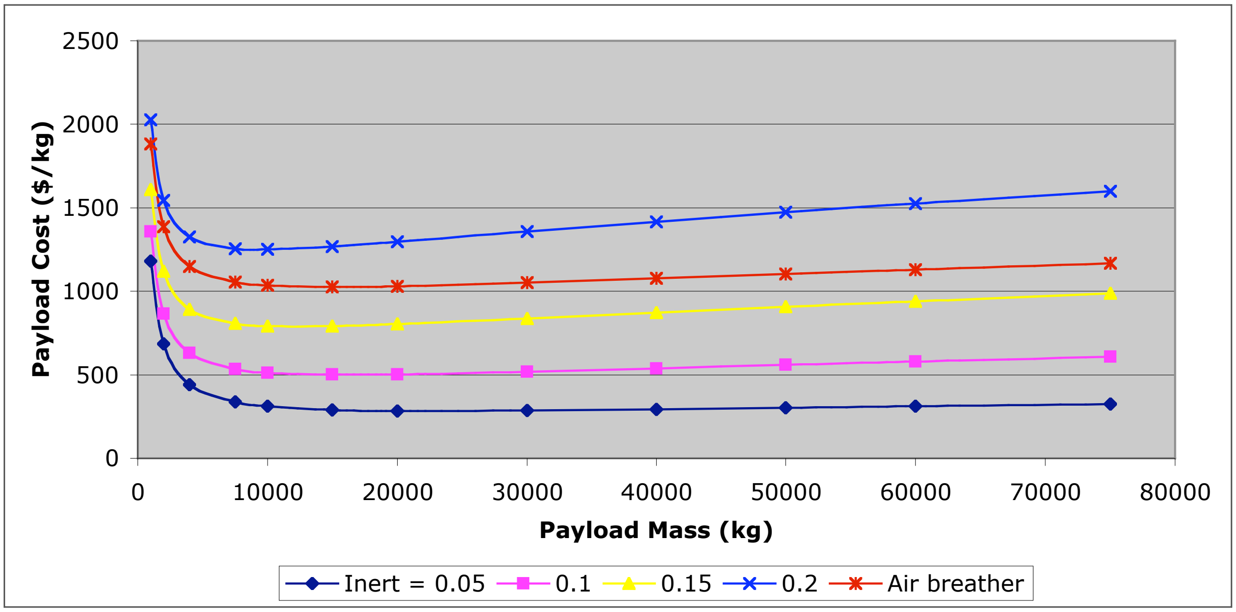

Figure 3. Inert mass fractions with air breather

Fig. 3 is similar to Fig. 1, but the latter now includes a set of data representing a vehicle with an air breathing first stage. This data is labeled "air breather" on the graph and is calculated using the assumptions for an air breathing stage stated above. The airbreather is more costly than rocket based vehicles with inert mass fractions around 0.15 and below; however, it remains less costly than rocket based vehicles with inert mass fractions of 0.2 and above. The airbreather modeled here has a larger inert mass fraction (0.35) but the efficiency of the engine (fuel-specific impulse = 2000 seconds) keeps the overall vehicle size down, which in turn limits the vehicle cost elements and keeps the payload cost down.

B. Refurbishment Fraction and Number of Flights per Vehicle

Refurbishment costs are those costs associated with maintenance and repair on reusable vehicles between flights. The refurbishment fraction is defined as the percentage of the first unit production cost that is required for average post-flight refurbishment of a reusable launch vehicle for subsequent launches. A range of refurbishment fractions from 1-20% was considered. The current space shuttle orbiter generally falls into the 10-20% range for refurbishment fraction. As can be seen from Figure 4, increasing the refurbishment fraction of a vehicle increases the payload cost at any given payload mass. Even a high refurbishment fraction, such as 0.2, is still more cost effective than an identical expendable vehicle, represented setting refurbishment fraction to 0 and number of flights per vehicle to 1. The refurbishment fraction would have to be increased to the neighborhood of 0.4-0.45 for a reusable vehicle to become less cost effective than an expendable vehicle. This is due to the high production costs associated with expendable vehicles. The production costs of reusable vehicles are amortized over their lifetime due to multiple flights per vehicle. It should be pointed out that the specific comparison here is between identical reusable and expendable vehicles: this analysis does not take into account the fact that a reusable vehicle is inevitably lighter in weight due to the lack of need for carrying recovery systems, nor that reusable vehicles typically require more advanced technologies for viability, thus requiring a cost premium for both nonrecurring and recurring costs at the same physical size as a corresponding expendable vehicle. These effects will be addressed in the future continuation of this research.

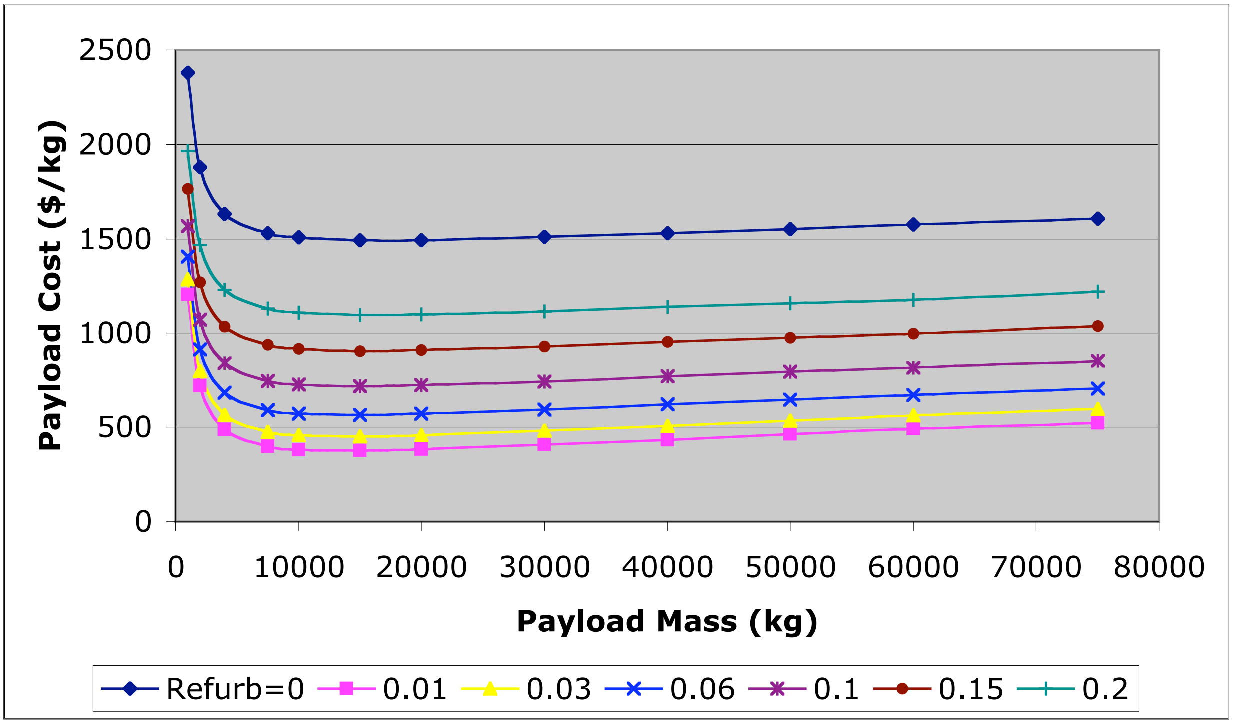

Figure 4. Effect of refurbishment fraction on payload cost

An interesting complement to the refurbishment fraction is the number of flights flown per vehicle. While it might intuitively seem that one would always want to fly a reusable vehicle as many times as possible, analysis indicates that, beyond a certain point, the reusable vehicle fleet size becomes so small that almost no advantageous effects of the learning curve are achieved. Taken to the extreme, if one vehicle could fly every mission in the program, it would be a "hand-built" vehicle, with corresponding high costs for refurbishment parts.

To better understand the effects of number of flights per vehicle on the payload launch costs, sensitivity analysis was run to optimize the optimum number of flights per vehicle for each of a range of refurbishment fractions. First a baseline case of a TSTO vehicle with δ_1=δ_2=0.12 and I_{sp1}=I_{sp2}=450 seconds was established. The results are shown in Table 2 below.

f_{refurb}	Optimum N_{fpv}	Optimum Payload Size	Optimum *dv* split	$/kg at Optimum Payload
0.01	215	13700	0.625	314
0.03	72	14000	0.622	432
0.05	43	14200	0.621	524
0.07	31	14200	0.620	605
0.1	21	14400	0.619	714
0.15	14	15000	0.619	874
0.2	11	15400	0.618	1017

Table 2. Refurbishment fraction and flights per vehicle at δ=0.12 and I_{sp}=450

This analysis shows that low refurbishment fractions (with correspondingly low refurbishment costs) optimize to a large number of flights per vehicle. Given the relatively low refurbishment costs, there is a clear benefit to a long vehicle lifetime as it allows the amortization of nonrecurring costs over a large number of flights. As the refurbishment fraction moves into the shuttle range (0.1~0.2), the optimum number of flights per vehicle drops precipitously, into the range of only 10-20 flights per vehicle. In all cases, refurbishment costs are a substantial portion of the overall payload launch costs, as reducing refurbishment rates dramatically reduces overall payload costs. The other significant trend from Table 2 is that there is very little difference across the cases in absolute optimum payload mass or in the velocity increment at staging conditions. While these parameters are still included in all subsequent analyses, the values for these second-order variable results will not be further documented in this paper; instead, we will focus on trends in cost per kilogram of payload, along with number of flights per vehicle to produce the minimum payload charges. Using refurbishment fraction as the independent variable, the trends relating optimum number of flights per vehicle with payload costs are shown in Fig. 5.

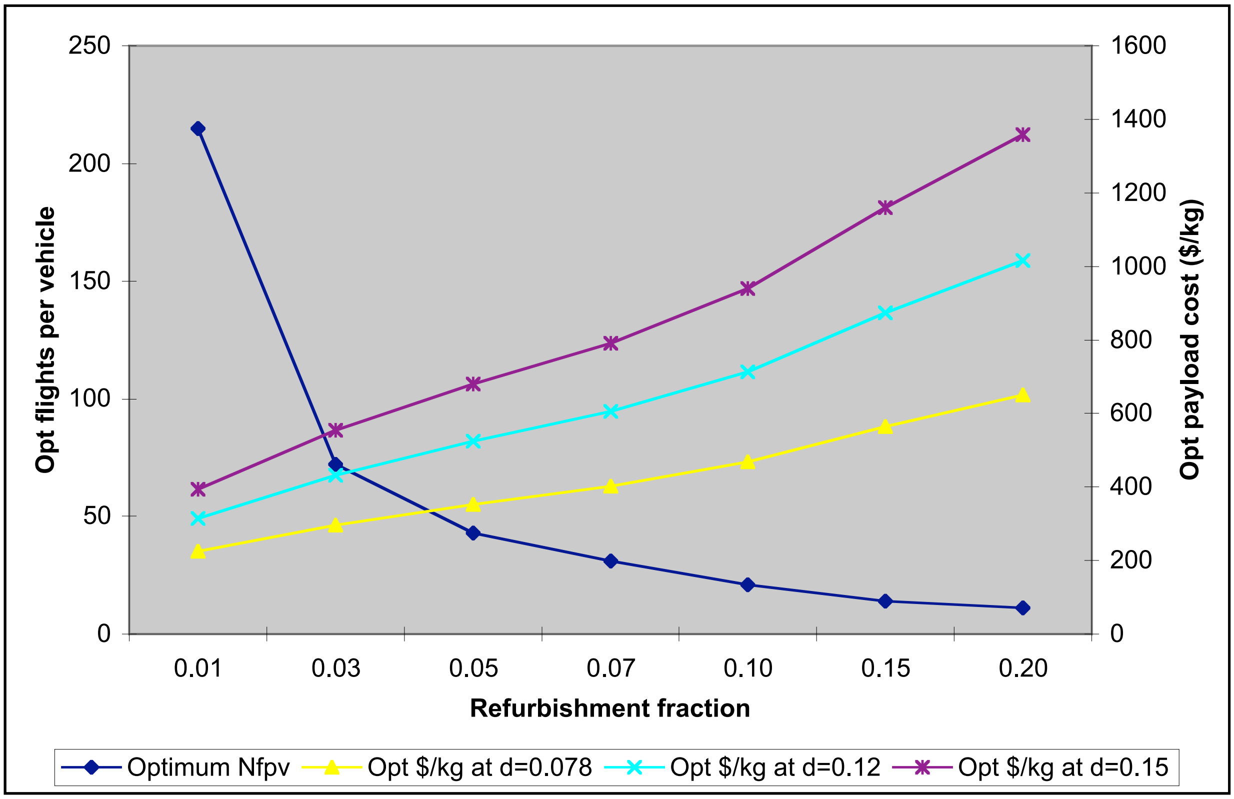

Figure 5. Refurbishment fractions and flights per vehicle at δ=0.078, 0.12, 0.15 and I_{sp}=450 sec

To determine the effect of changing inert mass fraction on the relationship between refurbishment fraction, N_{fpv}, payload size, payload cost and dv split, a sensitivity analysis was performed by raising and lowering the values for δ by a set factor. From the baseline value of 0.12, δ was lowered to $\delta_1=\delta_2=0.078$, and then raised to 0.15; throughout these trials, the specific impulse was maintained at $I_{sp1}=I_{sp2}=450$ seconds.

Similarly, to determine the effect of changing I_{sp} on the relationship between refurbishment fraction, N_{fpv}, payload size, payload cost and *dv* split, the specific impulse values were set altered from the baseline I_{sp} to $I_{sp1}=I_{sp2}=320$ seconds while holding $\delta_1=\delta_2=0.12$. The results are shown below in Fig 6.

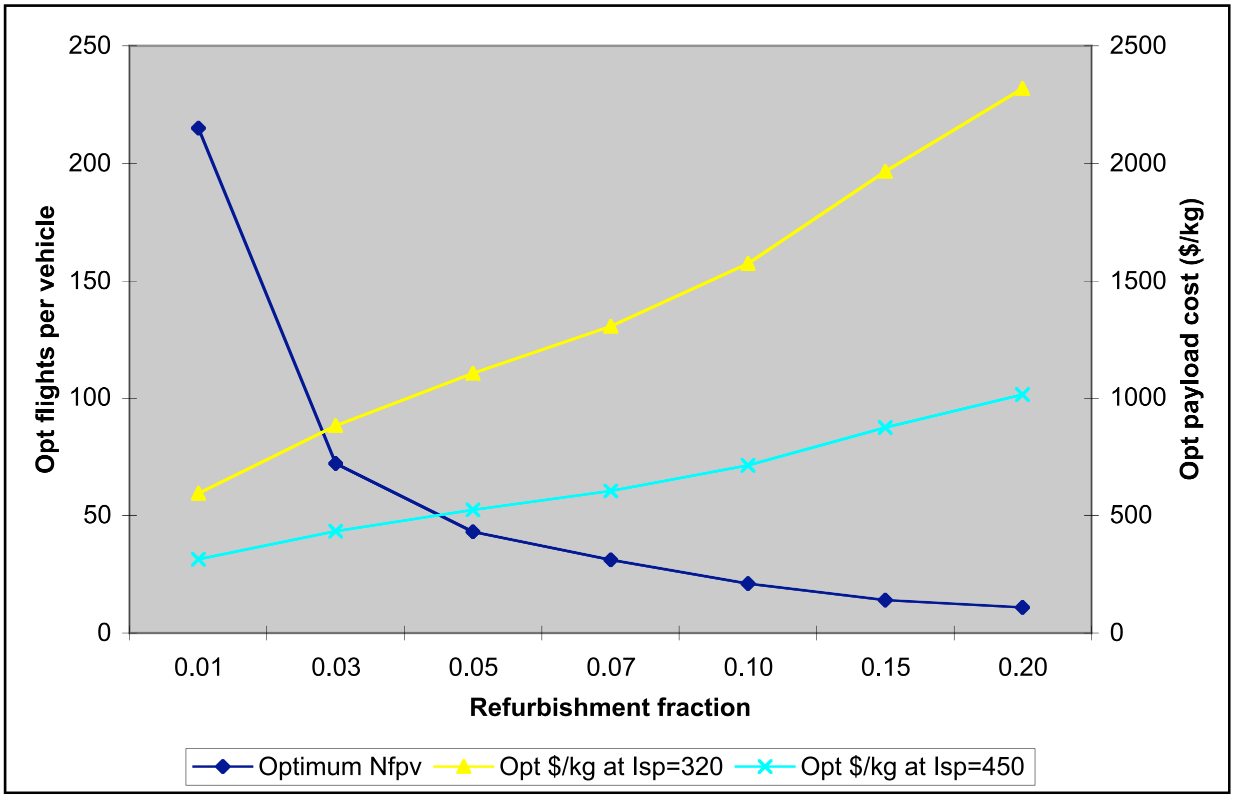

Figure 6. Refurbishment fraction and flights per vehicle at δ=0.12 and I_{sp}=320, 450 sec

These sensitivity analyses show that changing δ and I_{sp} does not have any effect on the optimum number of flights per vehicle for a given refurbishment fraction. Also, the optimum payload size stays nearly constant throughout, with only a few hundred kilograms variation across the various analyses. However, the payload costs per kilogram change dramatically, which illustrates the critical importance of refurbishment fraction on launch costs.

As mentioned earlier, there is a direct correlation between the refurbishment fraction and the optimum number of flights per vehicle. These optimum number of flights per vehicle at a given refurbishment fraction is constant as the inert mass fraction, specific impulse or *dv* split change.

The optimum number of flights per vehicle decreases as refurbishment fraction increases, due to the learning curve impact of extremely small fleet sizes and corresponding production runs. Since refurbishment fraction is a function of first unit production costs, refurbishment fractions as a cost driver are scaled with the overall size of the vehicle. Vehicles with a high refurbishment fraction have a higher payload cost than vehicles with a low refurbishment fraction. At currently demonstrated refurbishment rates (10-20%), vehicle maintenance actions following each flight are a significant fraction of the costs to build the first vehicle. Unlike increasing the size of the production run, however, refurbishment costs (as evidenced by both the X-15 and Space Shuttle programs) evidence much lower rates of learning effects than vehicle production. Therefore, to reduce costs for a vehicle with a high refurbishment fraction, it is advantageous to reduce the number of flights flown by each vehicle to increase the size of the fleet production run, which in turn reduces both the cost per vehicle and the cost of necessary spares for the refurbishment process. One corollary of this observation is that the payload size increases, the optimum number of flights per vehicle decreases. Higher vehicle production and flight rates for the program as a whole (as opposed to any single vehicle) still are the most important factor in minimizing payload launch costs.

C. Future Studies

A number of directions for further analysis are evident. Although there are no statistically significant trends to inert mass fraction as a function of vehicle gross lift-off mass, an intuitive examination of the regression analysis shows that there could be some reason to at least examine the effect of an economy of scale for vehicle inert mass.

This will significantly complicate the analysis over the current assumption of constant d, and should be analyzed to better understand the effect on optimum vehicle sizing.

This paper focused on reusable two-stage vehicles, and only touched the surface of design issues related to advanced systems such as airbreathing propulsion systems. Based on the simple vehicle-level parametric analysis presented in this paper, it is possible to more rigorously review various options in vehicle design, including mixed options such as reusable/expendable stage combinations and the effect of airbreathing staging delta-V.

Even the current analysis shows that, while reusable vehicles appear to be lower cost than expendables, the absolute differences in costs between them are not that large. Expendable vehicles offer further advantages over the reusable systems examined here in terms of lower mass fractions and lower technology levels, which translate to lower costs per kilogram of inert mass for both nonrecurring and production costs. These effects need to be quantified and modeled, and the data used to reexamine the trades between expendable and reusable vehicles.

The current study has shown the critical effects of learning curves, which are the driving effect towards smaller vehicle sizes in order to increase production and flight rates. One strategy to increase production run sizes is to adopt modular vehicle practices, as in the three identical common booster core modules of the Delta IV Heavy EELV. Rather than a single monolithic first stage, three identical modules reduce the total unique inert mass in the first stage (thus decreasing both nonrecurring and first unit production costs), as well as tripling the size of the first stage production run for a given number of launch vehicles produced. Other concepts in modular launch vehicles, such as the OTRAG vehicle concepts from the 1970's, dramatically reduced the unique design mass by adopting designs with large numbers of identical modules. This approach should be better modeled and compared directly with more conventional designs, both reusable and expendable.

Modularity becomes even more important when time effects of money supplies are considered. Cost discounting is the traditional analysis technique to incorporate the opportunity costs of investing, wherein deferring expenditures is preferable to making payments in the early years of a program. Particularly for commercial launch vehicle programs, the traditional high nonrecurring costs of a space vehicle have prevented the levels of return on investment currently expected by venture capitalists. Incorporating the effects of cost discounting at various interest rates will further increase the bias towards smaller and more inexpensive launch vehicle flown in greater numbers, as well as increase the attractiveness of modular design concepts.

V. Conclusion

This cost model determines the critical parameters in optimizing payload cost to LEO. Findings show that individual vehicle lifetime (optimum number of flights per vehicle) is a strong function of refurbishment fraction. For shuttle class refurbishment fractions of 0.1-0.2, the optimum vehicle lifetime can be as low as 10-20 flights. At higher flights rates, the increasing refurbishment costs puts maintaining these vehicles at an economic disadvantage as compared to retiring vehicles earlier to support a larger total production run. Published references have cited an inert mass fraction advantage for larger launch vehicles; a historical regression analysis does not show this to be statistically supportable, although subjective examinations of the data sets provide an intuitive support for further examining the effects of this possible trend.

The cost optimum solution tends to be for lower payload sizes and higher production and flight rates as the most effective means for keeping overall program costs low. Cost discounting, learning curve effects and modularity will all reinforce this trend, and need to be further examined to determine the optimum applications of each of these mitigation strategies to determine the ultimate limits of low-cost launch to orbit based on rocket and airbreathing propulsion technologies.

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