Probabilistic Assessment of the Space Tourism Industry

What Will it Take to Make it Profitable?

AE8900 MS Special Problems Report
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Acronyms

IOC	Initial Operating Capability
NPV	Net Present Value
IRR	Internal Rate of Return
ROI	Return on Investment
MTBF	Mean Time Between Failure
CER	Cost Estimating Relationship
CABAM	Cost and Business Analysis Module
PDF	Probability Distribution Function
CDF	Commercial Development Factor

1.0 Introduction

Forty four years ago Yuri Gagarin became the first person to travel into space; this sparked a heated “space race” between the United States and the Soviet Union which ended with the historic moon landing in 1969. This began the world wide love for space travel and sparked interest in a possible future space tourism industry. It has taken nearly 35 years, but the space tourism industry has finally matured. With the successfully launch of SpaceShipOne, which captured the X-Prize in October of 2004, a vehicle is now finally available that can provide affordable access to space. Virgin Galactic has bought the rights to this design and will begin offering sub-orbital space flights in 2007 for a ticket price of around $200,000.

The goal of this study will be to determine the economic viability of the future space tourism industry. The study will include an economic evaluation of the currently proposed SpaceShipTwo Virgin Galactic partnership that will begin providing sub-orbital space flights in 2007. A second study will then be preformed to characterize a vehicle configuration and economic business model that will be most profitable in this space tourism industry. These models will be analyzed using LMNoP, an economic business case analyzer developed in the Space Systems Design Lab to predict the economic viability of a space tourism business model. Probabilistic analysis will be used to help provide greater confidence in the results then could be achieved through a deterministic result. It is the hope that the result of this study will help to establish a baseline economic model for a successful space tourism industry and will provide proof that this industry is within reach.

2.0 LMNoP Economic Model Update

Launch Marketing for Normal People (LMNoP) is a stochastic economic analysis tool developed in the Space Systems Design Lab to facilitate in understanding the economic impact of a vehicle design on the space tourism market. LMNoP is setup as a series of Excel spreadsheets that take in basic vehicle characteristics such as the vehicle gross weight, dry weight, passenger capacity, and reliability along with basic program information that includes the initial operating capability (IOC), program length, and desired ticket price. From these inputs LMNoP calculates the total number of passengers willing to travel at that ticket price, models the effects of possible vehicle failures, and develops a cash flow analysis for the entire program which includes a net present value (NPV), internal rate of return (IRR), and a return on investment (ROI) calculation. These figures of merit allow the designer to evaluate the economic attractiveness of different space tourism vehicles and/or programs.

LMNoP utilizes Monte Carlo probabilistics to treat uncertainty in both the baseline passenger demand and economic inputs (DDTE, TFU, and recurring cost). The Monte Carlo simulations generate distributions and allow for certainty levels to be determined on the economic figures of merit. A more detailed discussion of the different distributions applied and the certainty levels chosen will be discussed at a later point in this report.

LMNoPv1.4 was originally developed in 2000 by Dave McCormick, A.C. Charania, and Leland Marcus and used to investigate and quantitatively model the driving economic factors and launch vehicles characteristics that affect a business entering the space tourism market. These results were presented at the 51st International Astronomical Congress. The following section outlines the updates made to LMNoPv1.4 [1].

2.1 Market Demand Curve Update (Futron Market Study)

The market demand curve is the most important component of the LMNoP economic model. It provides a link between the ticket price and the amount of revenue that is generated for the given economic scenario. The model itself it very basic, it simply utilizes a curve fit of the annual number of passengers willing to pay a particular ticket price for a specified mission. These missions include sub-orbital, a single Earth orbit, multiple Earth orbits, and docking with an orbiting space station. The demand curves for each of these missions can be seen in Figure 1, along with the curve from the original version of LMNoP.

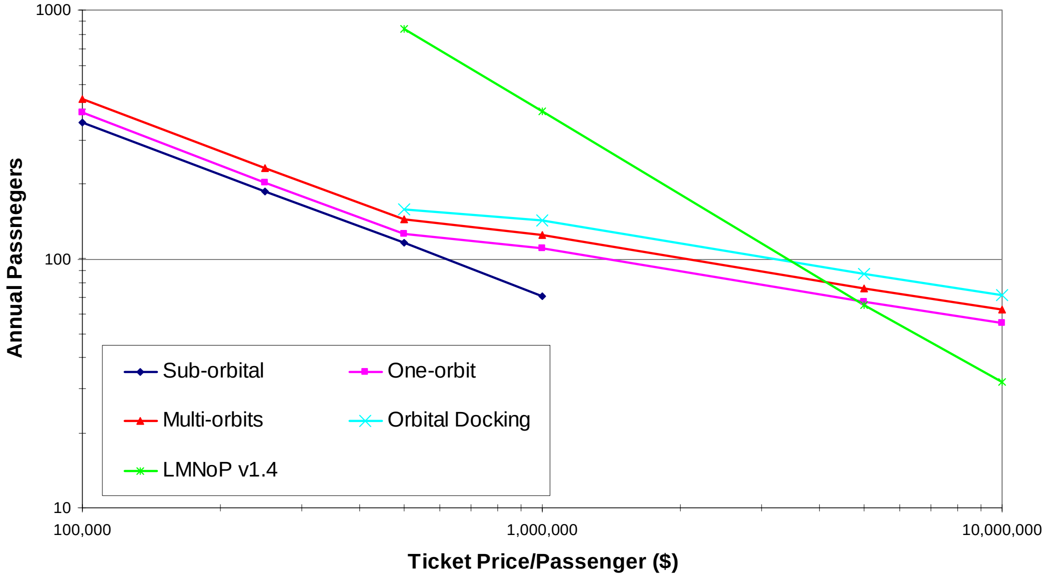


Figure 1: LMNoP Baseline Market Demand Curves.

The data for these curves was obtained from a study conducted by the Futron Corporation in October of 2002 [2]. This study attempted to characterize the future space tourism market by establishing a passenger demand model for the period between 2006 and 2045. This model is different than many of the previously conducted studies in that it only included "potential" space tourist. A "potential" space tourist as defined by The Futron Corporation is a person who meets the following three criteria. They must be able to withstand the physical and physiological stress associated with space flight. The physical training required would be similar to basic military training. They must be able to commit to a certain amount of training before being certified to travel into space. Futron estimates that this may be as little as a week for sub-orbital flights and as much as a few months for orbital flights. The final criteria restricted the survey respondents to those who could actually afford to pay the high ticket prices that will be associated with future space flights. These restrictions included a yearly income that exceeded $250,000 or an individual net worth of

$1,000,000. The application of these three criteria helped to limited the survey respondents to those who would be more likely to take part in future space flights and should provide more accurate data than previously conducted surveys.

Note that the demand data shown above is plotted on a Log/Log plot and that there is a much greater drop off in demand as the ticket price increases then is suggested by this figure. A more detailed example of how the demand changes with ticket price for the sub-orbital market is shown in Table I. The results of the sub-orbital market study will show that there is a ticket price within this range that provides a positive and optimal net present value for sub-orbital space tourism.

Table I: Sub-orbital Annual Passenger Demand.

Ticket Price ($)	Annual Passenger Demand
100,000	350
500,000	116
1,000,000	71

There is some concern with the accuracy of these results as it is very difficult to forecast a market that is currently not in existence. There are potentially very large errors in this data and the market could vary substantially from these values. How can a possible space tourism company invest millions of dollars into a launch vehicle without a better understanding of the available market? It is possible to understand the impact of changes in the market demand through the use of Monte Carlo simulations. Monte Carlo simulations allow LMNoP to apply triangular distributions to the demand curves to account for asymmetric variations in the baseline data. The triangular distribution allows the model to consider scenarios where the passenger demand can be greater or less then the baseline values. The model is then not run for a single point, but rather multiple times with the demand changing for every run. This allows for a confidence interval to be developed for the economic outputs of the model and a more robust decision can be made as to the economic viability of the particular scenario. An example of a confidence interval is shown in Figure 2, a ±15% triangular distribution is applied to the passenger demand model and a resulting distribution is obtained for the NPV where the blue region represents a 90% confidence that the NPV will be greater than $11.2 M (FY 2005).

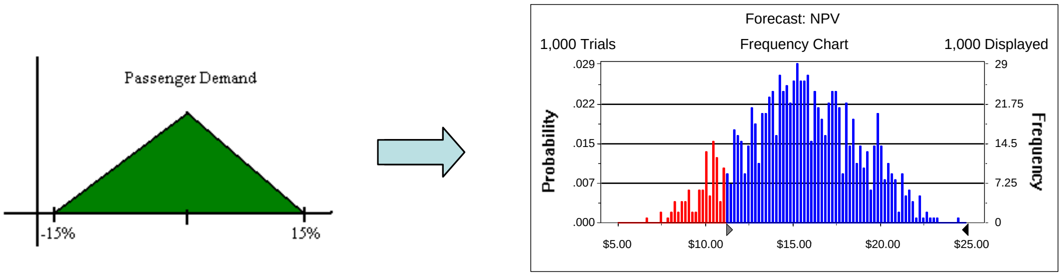


Figure 2: Monte Carlo Simulations.

The original LMNoP model utilized a hybrid set of data taken from the Commercial Space Transportation Study (CSTS) [3] and the work done by Nagatomo and Collins [4]. These studies were done in the early 90's and are over 10 years old, the Futron data provides a more current look at the possible passenger demand in addition to providing some insight into what a "potential" space tourism participant will look like. The Futron study provides a more up to date model for the baseline passenger demand.

2.2 Market Multipliers

The demand curves established in the previous section assumes that the passenger demand model is only a function of ticket price. This is not entirely the case; there are other factors that can affect this demand. The market multipliers attempt to alter the baseline passenger demand model to account for changes in the vehicle concept of operations. The original version of LMNoP included five multipliers that would affect the baseline demand curve. The ability to accurately model the effects of these multipliers was not available in the original version and simple factors with a scale of 0.5, 1.0, 1.5, and 2.0 were used to distinguish between the different categories. The current version of LMNoP attempts to more accurately model the effects of each of these multipliers. Jane Reifert, president of Incredible Adventures provided a great source for helping to understand the effect that each of these multipliers would have on the potential space tourism market [5]. Her experiences with high risk, adventure seeking customers provided a unique insight into the mind of the potential space tourist. The following sections outline the original five market multipliers and how they have been updated in the current version of LMNoP.

The visibility multiplier defines the viewing experience that each passenger receives during the flight. This is a direct factor in the design of the vehicle and is represented by the size of the viewing area provided for each passenger. The four categories are show in Table II.

Table II: Visibility Definition.

Category	v1.4	v2.0
Multiple People/ Window	0.5	0.25
Small Window /Person	1	0.9
Large Window / Person	1.5	1
Glass Ceiling	2	1.25

The changes to the visibility multiplier came as a result of a better understanding as to the importance in the ability to view the earth from space. Ms. Reifert suggested that this would be the selling point as many future space tourism designs would require passengers to remain seated during the flight. Therefore the baseline design would require a large window to be available to every passenger. If space tourists had to share their view then there would be a very large decrease in the number of passengers willing to fly, it was estimated that this effect would decrease the market by as much as 75% from the baseline market demand for any given ticket price.

The comfort multiplier, shown in Table III were used in the previous version of LMNoP to account for the idea that passengers would be willing to pay a higher price for a more comfortable experience. This effect would be similar to that seen in the airline industry today. First class passengers are will to pay a higher ticket price for a large more comfortable seat during their flight. It is doubtful that a similar result would be seen in future space flights. Ms. Reifert stated that she has never had a complaint about the comfort level on one of their jet fighter experiences. She did point out the importance of designing the vehicle to accommodate for all different size and shapes of passengers as that would limit the number of passengers more than the comfort of the seat. This multiplier was removed from the current version as it was unlikely to play a large role in affecting the size of the passenger demand.

Table III: Comfort Definition.

Category	v1.4	v2.0
Sub-Coach	0.5	1.0
Coach	1.0	1.0
Business Class	1.5	1.0
First Class	2.0	1.0

The duration multiplier allowed for the original version of LMNoP to account for varying mission types having different passenger demands. This was needed in the original version because there was only data available for an orbital docking mission and the multiplier was used to calibrate the demand curve for the various other missions. The LMNoP model now has a demand curve for each of the four mission types. Therefore the demand curve multiplier was removed form the LMNoP model.

The location demand multiplier accounts for an increase in the demand that would occur if multiple launch sites are available. The original version of LMNoP assumed that this meant multiple locations within the United States; however, the general space tourist would not be driven by the location of the launch facility. The general space tourist would likely be a world traveler and would be very willing to travel to reach the launch facility. This would indicate that multiple locations within the United States would not increase the demand by any significant amount. If there were launch locations available outside of the United States this could likely lead to a very large increase in the number of passengers willing to travel into space. Obtaining a visa to enter the United States is becoming increasingly difficult and could hinder sales to foreign nationals. Operating facilities in the European Union or Asia could greatly increase the demand. The effect of overseas operations on the demand curve is shown in Table IV below. A multiplier of 1 indicates a single launch location within the United States.

Table IV: Launch Location Multiplier.

Non - US Locations	Multiplier
0	1
1	1.5
2	2
3	2.25

The expansion multiplier suggests that there will be an in increase in the baseline passenger demand from year to year while the ticket price remains constant. This increase in passenger demand comes from an increase in interest that is likely to be seen as more and more tourists travel into space. The perceived risk will begin to decrease and the overall popularity will begin to increase causing an increase the demand for space flights. This increase in demand is modeled after an S-curve where there is a small expansion at the beginning and end with rapid expansion in the middle. This S-curve developed for the LMNoP model is provided in Figure 3. The user inputs the expected increase after 40 years of space tourism operation, in this case the increase is 4x.

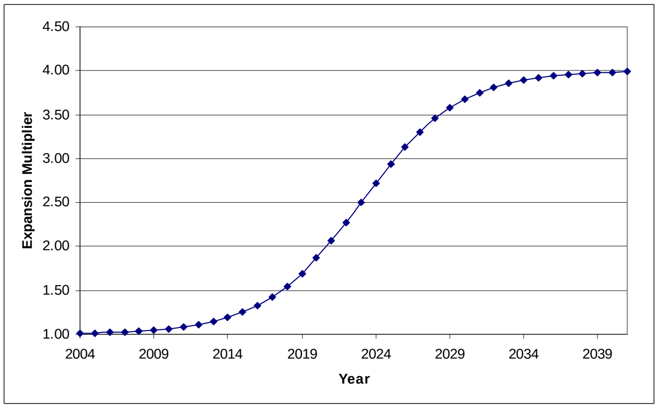


Figure 3: Market Expansion S-Curve.

These three remaining market multipliers, visibility, foreign launch site locations and market expansion are applied multiplicatively to the baseline passenger demand and a final annual passenger demand is determined.

2.3 Reliability Model

The reliability model implemented in LMNoP attempts to model the effect that a vehicle failure, and subsequent loss of passengers would have on the overall economic model. The overall vehicle reliability is modeled using an exponential distribution, with the assumption that the chance of failure remains constant over the life of the vehicle. The probability (P) is the probability that there will not be a failure or a specified number of flights this is provided in equation (1) where the mean time between failures refers to the estimated number of flights before a vehicles failure occurs, i.e. 1/1000.

$$P = e^{-\frac{t}{MTBF}} \tag{1}$$

This equation can be further expanded until this becomes a function of the number of flights/vehicle and the overall reliability of design. This expansion is given by the following equation.

$$P = e^{-\frac{t}{MTBF}} = e^{-\frac{Flights}{Vehciles}\Big/\frac{1}{1-R}} \tag{2}$$

A random number is then generated to determine if a failure occurs in the given year. The yearly chance of failure is independently calculated for each year of the program. An example of this calculation is provided below. Determine the probability of no failure occurring after 200 flights at a vehicle reliability of R = 0.999 and R = 0.998.

$$P = e^{-\frac{200}{1000}} = 0.819 \quad R = 0.999 \tag{3}$$

$$P = e^{-\frac{200}{500}} = 0.670 \quad R = 0.998 \tag{4}$$

There is an 18% chance that one or more failures would occur within 200 flights for a reliability of 1/1000, and a 33% chance for a reliability of 1/500.

The above equations predict whether or not a failure occurs within a given year, but what happens if a failure does occur, what is the effect on the market demand? If a failure does occur then it would be expected that there would be a decrease in the number of passengers willing to fly in the following years as many passengers would question the safety of the vehicle. It would take a series of flights, without incidence, before full confidence was restored and the market returned to normal operations. LMNoP models this loss of demand with a recovery period following a vehicle failure. The first year is the year of failure and all flights are assumed to be canceled while safety measures are taken to ensure that no future failures occur. The following four years go through a market recovery period where the market returns to 50% of its pre-failure levels in the 2nd year and slowly gains back the remaining market by the beginning of the fifth year. An example of this is shown in Figure 4. The y-axis indicates the percentage of the market that is currently willing to partake in space flights.

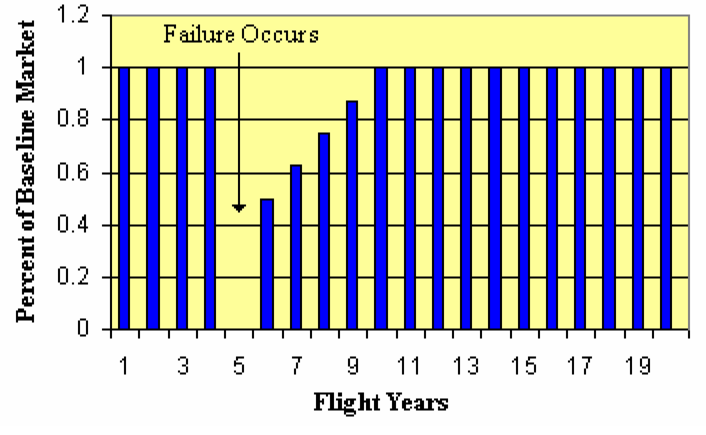


Figure 4: Single Failure and Recover Period.

The reliability model also assumes that a space tourism operator can not tolerate two failures within close proximity. If a vehicle has a second failure within the recovery period then the company is shut down, this could be due to government restrictions or just a complete loss of the entire market. An example of this is shown in Figure 5.

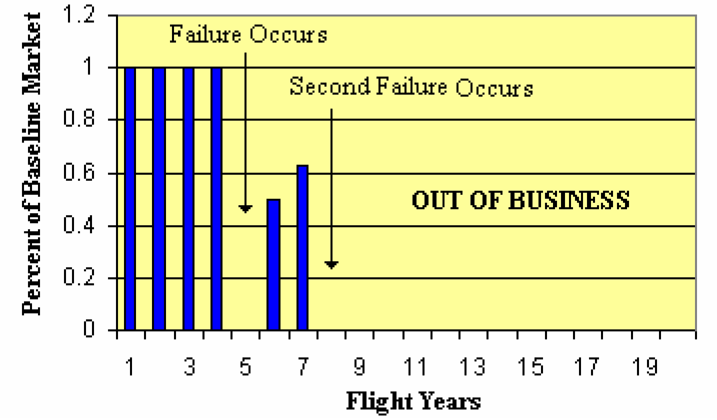


Figure 5: Double Failure Results in Going out of Business.

An attempt was made to try and more accurately model this recovery period using airline data from the recovery period that followed September 11, 2001. This attempt failed as the recovery period for the airlines was much quicker than expected, reaching 90 – 100% of the original levels within a few months. This is probably due to the fact that the majority of daily flights are business and not leisure travel related. A failure relating to space travel would likely have a much greater drop off in demand. The effects of a vehicle with a non-zero chance of failure will be discussed in later sections of this report. It will be shown that this is an important driver in the overall design of a space tourism program.

2.4 Cost Model

There was no cost model built into the original version of LMNoP and the values for the development, production, and operations costs were simply input into the model. These are three of the most important factors in determining the economic viability of the program. It would be valuable to develop a model that will allow these values to be calculated within

LMNoP while still keeping the vehicle design at a top level. This will be accomplished by using a modified version of Dr. Robert Goehlich's SUBORB-TRANSCOST [6] and a commercial development factor that can be applied to the NASA-developed CERs to help predict the development and production cost for a commercially developed vehicle.

The SUBORB-TRANSCOST model developed by Dr. Goehlich was derived from the Statistical-Analytical Model for Cost Estimation (TRANSCOST). The SUBORB-TRANSCOST model is applicable for single, first, or second stage winged and ballistic vehicles. Each vehicle can be created with jet engines, rocket engines, or both. The model takes into account the different number of vehicle reuses, jet engine reuses, and rocket engine reuses, which strongly influence the total operating costs. The model also calculates the development and production cost associated with each vehicle's stage and engine developed. The model also calculates the fixed and variable recurring cost associated with operating the vehicle. An example of how the operations cost breakdown is shown in Figure 6. The major contributors to the recurring cost are the cost associated with preparing the vehicles for launch, the cost associated with performing the mission, and the administrative cost required to operate a space tourism company. These costs make up 85% of the total recurring cost.

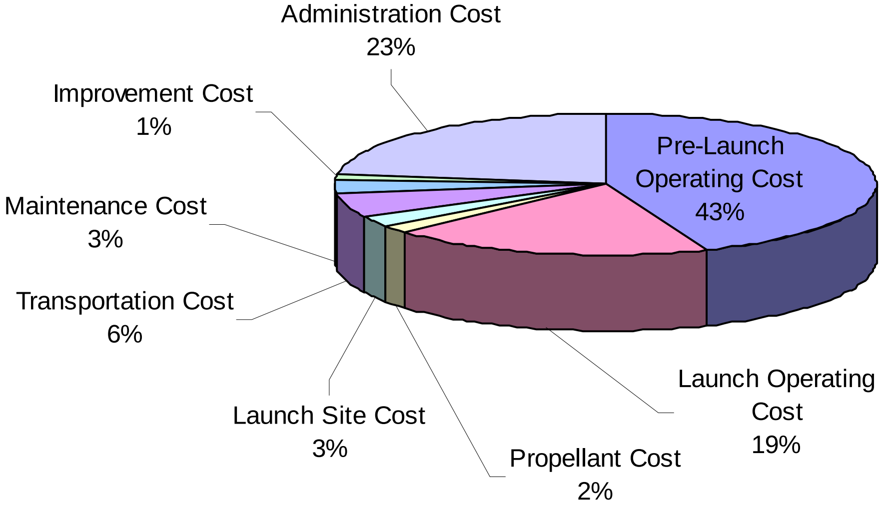


Figure 6: Sub-orbital Recurring Cost breakdown.

The operational costs are strongly dependent on the size of the vehicles, the number of flights flown/year, and the mission length. As the vehicle increases in size and the number of flights decreases the operational costs increase, this is indicative of a sub-orbital vs. orbital vehicle. The sub-orbital vehicles should have a lower gross weight because it has a less demanding mission then what is required for an orbital mission. The sub-orbital mission should also have a greater yearly flight rate because the ticket price for a sub-orbital mission is much less then that for an orbital mission and so the demand for sub-orbital flight should be greater. This lower gross weight should decrease the development cost and the increased in flight rate will provide for a lower operations cost. These trends provide evidence that this model is capable of predicting the operational cost for both sub-orbital and orbital missions. For the orbital missions the major contributors are the same as in Figure 6, but the launch operating cost is a larger percentage of the total operating cost.

The cost estimating relationships (CER) used in this model are based largely on NASA sponsored projects that have been developed over the last 40 years. These projects generally carry development cost in the hundred of millions to billions of dollars. This is counter intuitive to most commercially developed projects as cost is generally a driving factor in the design. If the development cost for a space tourism vehicle were in this range then an economically viable market could never be developed. It would seem very likely that if a launch vehicle was commercially developed for space travel then the development cost would be much less then what the NASA based CERs predict. This was proven to be correct by the development and successful launch of SpaceShipOne in October 2004. The total development cost was estimated to be between 20 – 30 $M, this is more then an order of magnitude less then what the NASA based CERs predict. There is also evidence that other small commercial launch companies such as SpaceX and Microcosm can develop launch vehicles for substantially less then what is predicted by the NASA-developed CERs. This information indicates that the historical based CERs are not applicable to newly developed small commercial projects and a new method needs to be developed to help predict theses development cost.

The benefit of having the NASA CERs available is that they have already been developed for many different vehicles types and there is a relatively large database to pull information from. So if these curves could be adapted to a commercially developed program, that would be very useful. This can be done through the use of a commercial development factor (CDF) that can account for the decrease in overhead, regulation and margin that is generally associated with a government program. The methodology in developing the CDF is to compare the development cost for a set of commercially-developed vehicles to what these CERs predict. This will provide a conversion factor to convert from a government developed vehicle to a commercially developed vehicle. This can then be applied to the TRANSCOST space tourism cost model. It is the hypothesis of the author that applying this factor to the development cost of space tourism vehicles provides a more accurate prediction of these cost then what current models predict. If these low cost can not be realized then the space tourism is unlikely to mature and the results of this report are not applicable.

The commercially developed vehicles used in this calculation are provided in Table V. This table also shows the actual/predicted development cost [7], the development cost as predicted by NASA's launch vehicle stage CER [8], and the TRANSCOST ballistic rocket CER [9]. These vehicles were selected because they are being developed to provide a new low cost launch alternative, and it is assumed that the development of a space tourism vehicle would have similar cost constraints, objectives, and compete is a similarly competitive market. The gross weight was used instead of the dry weight because there was a better correlation between the gross weight of these vehicles and their development cost.

Table V: development Cost Comparison.

	Gross Mass (kg)	Total Development ($M)	NAFCOM ($M)	TRANSCOST ($M)
SS1	8,260	25	n/a	n/a
Falcon I	26,133	75	971	1,830
K1	346,544	600	3,061	7,846
Sprite	38,020	75	1,435	3,158
Pegasus	21,911	53	1,046	2,044

The results shown in this table are not very surprising, the NAFCOM and TRANSCOST predictions are off by more than and order of magnitude for each of these vehicles. The results for these vehicles are provided with their corresponding curve fits in Figure 7. The actual development costs show a very good exponential trend with an R^2 value of 0.99. This curve also shows a similar trend to the other two CERs, with the gap between the two decreasing slightly as the size of the vehicle increases.

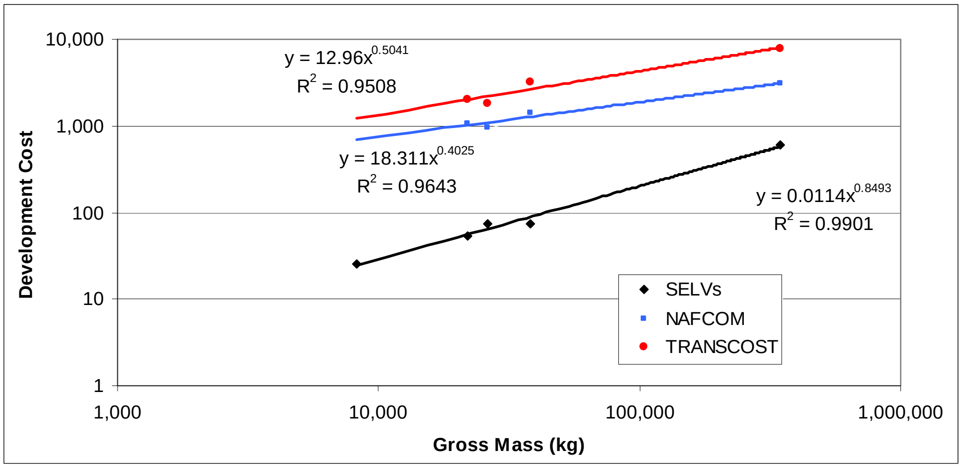


Figure 7: Small Entrepreneurial Launch Vehicle's Development Cost.

The development of the commercial development factor from these curves is shown below.

$$CDF = \frac{0.0114W^{0.8493}}{12.96W^{0.5041}} = 8.80x10^{-4}W^{0.345} \tag{5}$$

This factor is a function of the vehicles gross weight to account for the differences in the slope of these two curves. A set of example values for the commercial development factor are provided in Table VI.

Table VI: Commercial Development Factor Values.

Gross Weight (kg)	CDF
5,000	0.017
10,000	0.021
50,000	0.037
100,000	0.047

The cost model is one of the most important components of the LMNoP model and is the most difficult to determine highly accurate values. This poses a significant problem, because if the development or operating cost changes by 10% then this could throw off any predictions made by the economic model. In order to help alleviate this problem a similar probabilistic method as discussed previously is applied to the different costs values calculated from the LMNoP cost model. A triangular distribution is applied to the development, production, variable operating, and fixed operating cost. These distributions along with those applied to the passenger demand model generate the economic distributions as shown in Figure 2, these distributions are provided in Appendix A.

2.5 Debt Model

The debt model in LMNoP is setup as a matrix of the interest paid, the columns are the year in which the interest was paid and the rows are the year in which the loan was taken. This provides a convenient method to keep track of the company's current amount of debt and the interest paid, and for what loan it is associated with. The major change in the debt model for the current version of LMNoP is that the interest rate is not constant throughout the program, but is rather a function of the current debt. This is a more realistic model, because the more debt that the company has the greater the risk there is in providing a loan to that company. When the risk increases the corresponding interest rate will also increase, the increase will tend to plateau around and interest rate of 30%. The following table provides a sample of the interest rates as a function of the current debt.

Table VII: Interest Rate as a Function of Debt.

Current Debt	Interest Rate
$0 M	10.0%
$50 M	15.0%
$100 M	20.0%
$200 M	30.0%

2.6 Non-Constant Ticket Price

The original version of LMNoP only allowed for a constant ticket price to be charged throughout the program. This could cause misleading results as the ticket price effectively decreases from year to year due to inflation. It is also very possible that the ticket price would be reduced on future flights as space flights become more routine and the cost of doing business decreases. The current version provides the ability to change the ticket price from year to year to help model both of these effects. The model uses a simple linear relationship to change the ticket price from one year to the next. The inputs are the initial and final ticket price, and LMNoP determines the ticket price to charge in each year and the corresponding passenger demand. This provides more flexibility for the program manager and possibility a more optimized program.

2.7 Government Passenger Model

The addition of a the government passenger model provides the ability to model what would happen if a space tourism vehicle could also be used to transport government passengers (astronauts) to places like the International Space Station. The idea here is that a government passenger would be willing and is capable of paying a higher ticket price then that of a private individual. This model assumes that the vehicle developed already has docking capabilities and only slight modifications would be required to alter the vehicle for government passengers. It is up to the user to determine what additional costs would be required to upgrade the vehicle to accommodate government passengers, these cost are built into the model. The model assumes that NASA would just purchase a flight like any other customer, except that they would likely purchase all of the seats on a particular flight and just use the remainder of the vehicle capacity to transfer supplies. The government launch price curve was taken from the Cost and Business Analysis Module (CABAM) developed by the Space Systems Design Lab and derived from the Commercial Space Transportation Study predictions. The Launch price per available seat is shown in Table VIII for a range of required yearly launches. These prices are close to three times higher then the ticket price expected to be charged to private individuals, yet they are remarkably lower then what current estimates predict for the return of the Space Shuttle in 2005.

Table VIII: Government Launch Price.

Annual Government Launches	Launch Price ($M)
1	$35 M/Seat
2	$33 M/Seat
3	$31 M/Seat
4	$29 M/Seat
5	$27 M/Seat
6	$25 M/Seat

A further investigation will be preformed to see how the addition of government passengers effects the economic model of a space tourism docking mission. It looks like this would be a real benefit to both NASA and the space tourism operator if a vehicle can be developed to accommodate the needs and requirements of both.

3.0 Space Tourism Market Analysis Using LMNoP

The second part of this project is to investigate the economic viability of the space tourism industry. This includes a look into both the sub-orbital and orbital markets. The goals of this study will be to determine the optimized characteristics of a space tourism program. This optimization will be done for two different philosophies associated with the space tourism industry. The first philosophy states that a company capable of providing space tourism flights would do so in an attempt to generate a maximum profit for the company. This means that a company is more interested in an optimized economic scenario than they are in providing access to space for the general public. The second philosophy states that a company is more interested in providing a greater good to the general public than maximizing their return. This company is interested in maximizing the number of passengers flown while maintaining a minimum profit. The optimized program for these two philosophies is expected to differ substantially. The characteristics (LMNoP Inputs) of the space tourism program under consideration are the following:

1. **Vehicle's Passenger Capacity** – This will affect the overall size of the vehicle and therefore the initial development cost.
2. **Fleet Size** – This will effect the number of possible flights per year and the total size of the initial investments.
3. **Length of the program** – How many years the vehicle will operate.
4. **Initial Ticket Price** – Establishes the number of annual passengers.

These four characteristics provide the ability to setup a program cash flow and determine its economic viability. This will assume that the other vehicle factors such as turn around time and reliability, and the economic factors such as interest, inflation and discount rates remain constant among the different programs. A list of these values is provided in Table IX.

Table IX: Constant Program Factors.

Economic Factors	**Value**
Inflation Rate	3.0%
Tax Rate	30%
Discount Rate	17.50%
Interest Rate	Table VII
Vehicle Factors	
Turn Around Time	14 Days
Reliability	0.999/1.0

In order to measure the effect of the passenger capacity, a relationship had to be developed between the capacity of the vehicle and the total development cost. This could be done using the cost model if the weight of the vehicle was known as a function of the passenger capacity. A generic space tourism vehicle model was developed to help determine the relationship between the passenger capacity and the vehicle gross weight. This vehicle was modeled as a two stage, LOX/LH2 rocket powered launch vehicle and uses historical MERs to build up the vehicle weight. The vehicle was allowed to scale photographically in order to meet a given mass ratio. A break down of this vehicle is provided in Appendix B. A curve fit of the vehicle gross and dry weights were made as a function of the passenger capacity, all other vehicles inputs were held constant, these curves are provide in Appendix C. These curves were then put into the LMNoP cost model so that the vehicles development cost would change as a function of the passenger capacity. An example of this relationship is shown in Figure 8.

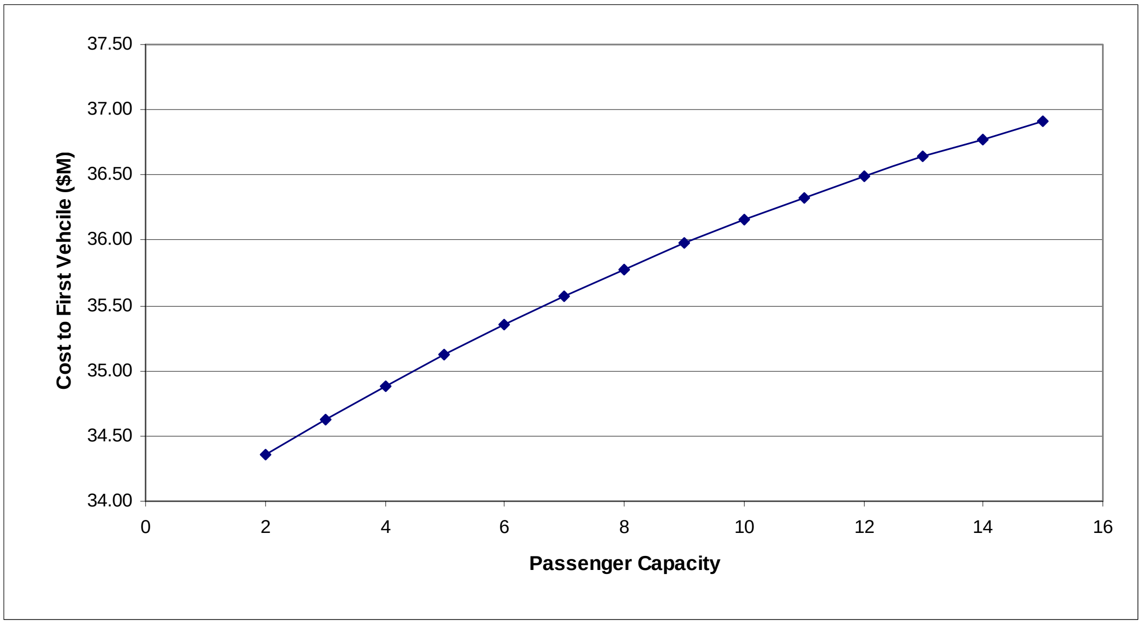


Figure 8: Sub-Orbital Cost to First Vehicle as a Function of Capacity.

In order to determine the set of characteristics that optimize the two philosophies disused earlier an optimization scheme needed to be employed. The two options considered were a Genetic Algorithm and a Full Grid Search. Both of these methods would be able to handle discrete and integer values. The full grid search would look at every possible combination of the four characteristics listed above; this was initially estimated to be 6,160 combinations. The GA would likely decrease the number of runs to fewer than 2,000. Since each of the simulations is run probabilistically and require approximately 5 seconds to complete the GA provides the possibility of six hours of time savings. The problem that was encountered when running the simulations is that the results could vary from one run to the next, due to the stochastic nature of the problem. In addition to this a certain set of combinations resulted in very similar objective functions, results that different by less then 5%. In general there were a collection of results that were within a few percent of the best objective function. It was difficult to determine if the GA correctly considered the entire design space and where or not it look at all the possible configurations that were within this small percentage of the optimal design. It was therefore decided that a grid search would provide a more complete look at the entire design space. It would require a longer run time, but once it was complete the entire design space would be available and a ranking of the top choices could be made. In order to decrease the run time a smaller ranges were used for each of the design variables. The final ranges investigated are shown in Table X and represent about 1,500 combinations.

Table X: Ranges Used for Program Factors.

	Capacity	Program Length (yr)	# of Vehicles	Ticket Price ($M)
Sub-Orbital				
Max: Net Present Value	5 – 10	5 – 12: R = 0.999 12: R = 1.0	1 – 5	0.6 – 1.0
Max: Total Passengers	5 – 10	5 – 12: R = 0.999 12: R = 1.0	1 – 5	0.1 – 0.5
Orbital				
Max: Net Present Value	8 – 15	5 – 12: R = 0.999 12: R = 1.0	1 – 5	8 – 15
Max: Total Passengers	8 – 15	5 – 12: R = 0.999 12: R = 1.0	1 – 5	1 – 5

The following sections will discuss in detail the results of this study and how they compare to current space tourism programs. The following sections will look at the Virgin Galactic model as it is currently advertised, possible improvements that could be made to this model, effects of changing passenger demand on the Virgin Galactic model, and finally a general optimized sub-orbital and orbital space tourism market.

4.0 Virgin Galactic and SpaceShipTwo Market Study

Virgin Galactic will become the first commercial space tourism company to provide sub-orbital space flights when it begins operations in 2007 [10]. Virgin Galactic will operate a derivative of the historic SpaceShipOne. This vehicle has been coined SpaceShipTwo. Very little information is known about this vehicle, but what is known is that the vehicle will likely be a scaled up version of SpaceShipOne carrying 5 – 8 passengers and traveling to an altitude of 350,000 ft which should provide 7 – 10 minutes of weightlessness. Virgin Galactic has purchased the rights to SpaceShipTwo and placed an order for five vehicles to be built by 2007. The Virgin Galactic model consist of a $125 M investment, which includes $100 M paid to Scaled Composites for the development and production of five SpaceShipTwo vehicles, and a $25 M facilities development cost. Virgin Galactic plans to sale 3,000 tickets over 5 years of operation at a ticket price of $200,000. A summary of the Virgin Galactic model is provided in Table XI.

Table XI: Virgin Galactic Model.

Passenger Capacity	5 - 8
Altitude(km)	350,000
Weightlessness (min)	7 - 10
Ticket Price ($)	200,000
Investment Cost ($M)	125
Operating Cost ($/Flight)	0.55*
IOC	2007
Operating Years	5
Passengers / Year	600

* Calculated from the LMNoP cost model not provided by Virgin Galactic

The Virgin Galactic Model as described above will be investigated using LMNoP in order to determine the economic viability of the current program. The term "economic viability" refers to the ability to meet specific economic requirements. In this case the requirement for economic viability will be a net present value greater then zero. Slight changes needed to be made to the LMNoP model in order to accurately model the Virgin Galactic program. The most important was a increase in the market demand model that was needed to match the 600 passengers/year predicted by Virgin Galactic, this required a 3.1x multiplier on the market model within LMNoP as it only predicted 967 passengers/year. The discrepancies are large between the two models, this could be due to Virgin Galactic's advertisement that it will only operate for five years, this "limited time offer" would likely increase the demand as people would be concerned about possibly missing their initial opportunity. There may also be a push to be apart of the first group of space tourists, an excitement factor. This investigation will be done stochastically using the input distribution provided in Appendix A in order to provide a greater confidence in the results of this investigation; these results will be provided at a 90% confidence.

The reliability of SpaceShipTwo is not known and so the investigation will look at two possible cases in order to explore the sensitively to vehicle reliability. Case 1 will be a perfectly reliable vehicle (R = 1.0), and Case 2 will be a vehicle with a 1/1000 chance of failure (R=0.999). Case 1 will provide the best case scenario and Case 2 will provide insight as to how reliability affects the economic viability of the design.

4.1 Case 1 - 100% Reliability, Virgin Galactic Passenger Model

Case 1 assumes that SpaceShipTwo has 100% reliability and completes all 600 flights without incidence. This totals to 3,000 tickets over the course of five years for a total revenue of $600 M. This generates a Net Present Value of $15.1 M which suggests that this case is an economically viable program. In actuality there is a 100% chance that if there are no failures over the five years of operation that the Virgin Galactic program will be economically viable. Even for the worse set of noise variable, the highest development and operating cost, the program would still see an NPV of $7.5 M. This suggests that the program is very robust, as long as no failures occur. The probability density function (PDF) for the NPV is shown in Figure 9, the blue section is 90% confidence interval.

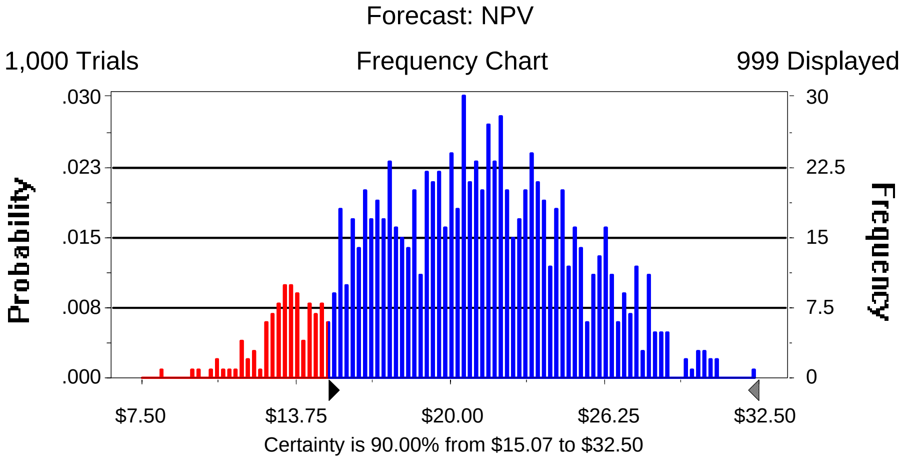


Figure 9: Virgin Galactic Results for R = 1.0.

The NPV evaluation helps to determine if an investment should be undertaken and is a good method to compare different investment options. It general it is difficult to understand what a NPV of 15.7 $M represents in terms of a cash flow, therefore it will be useful to look at the total profit, return on investment (ROI), and expect revenue for each program. The total profit is the final cash on hand at the end of the program after all expenditures have been paid, the ROI is the incremental gain divided by the total investment cost, and the revenue is the total amount of money generated.

$$ROI = \frac{\left(Revenue - Total \quad Cost\right)}{Total \quad Cost} x100 \qquad (6)$$

There is a 90% confidence that the Virgin Galactic model will generate at least a 16.9% ROI and a total profit of $81.6 M (FY 2005). These distributions are shown in Figure 10 below. A final profit of $81.6 M is small considering the size of the initial investment and the risk that is involved in operating a space tourism vehicle. A single failure could drastically effect the economic viability of this program. This effect will be looked at closer in next section. It is likely that there are other factors involved in Virgin Galactic's decision that are not addressed in this study, it seems that there is possibly a better solution to the sub-orbital space tourism model than one with such a small return.

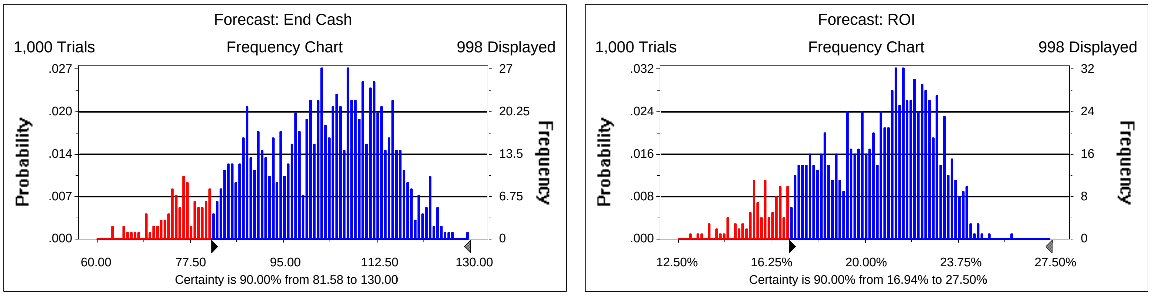


Figure 10: Virgin Galactic Results for R = 1.0 (Total Profit, ROI).

The yearly and cumulative cash flows are shown in Figure 11, these values are discounted at 17.5 % and presented in FY $2005. The initial investment is spread over the first three years while vehicles are being developed and built by Scaled Composites. Operations begin in year 2007 and last until 2011, the revenue and cost for these five years is the same, and the drop off that is seen is due to the inflation rate. The cumulative cash flow experiences a large drop due to the initial investment at the beginning of the program and then begins to rise once operations begin. The program breaks even somewhere between 2008 and 2009.

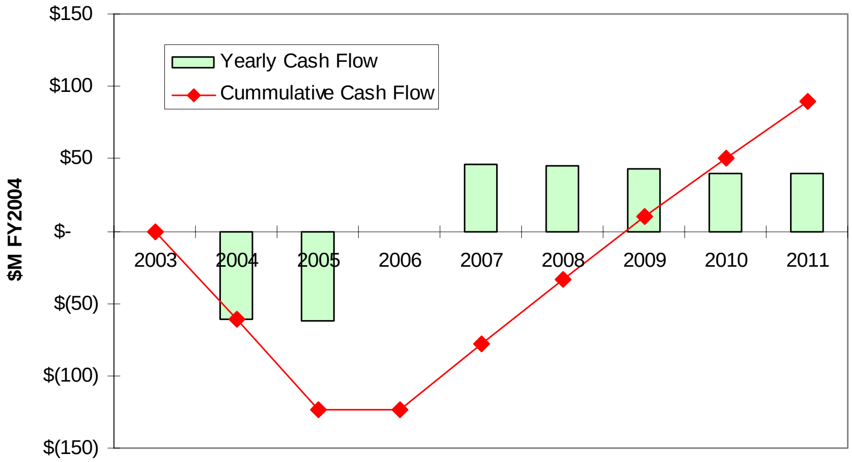


Figure 11: Virgin Galactic Discounted Cash Flow Analysis, No Failure (FY $2004).

4.2 Case 2 – 1/1000 Chance of Failure, Virgin Galactic Model

The second study of the Virgin Galactic model assumes that the vehicle reliability does not have a 100% reliability and that the vehicles will fail 1/1000 times. This equates to a reliability of R = 0.999. The Virgin Galactic model assumes about 600 flights over the life of the program so it is not expected to see a crash during every simulation. The total number of failures that occur during the 1,000 simulations is provided in Table XII. A failure occurs in about 40% of the simulations, when this occurs the reliability model begins to take effect. These effects include a complete loss of the market for the failure year, as the vehicle is being overhauled to determine the cause of failure. The years following the failure experience a decreased in demand as the market is regaining confidence in the vehicle, this recovery trend can be seen in Figure 4 and Figure 5 . There is also an insurance premium that must be paid along with legal fees and any cost associated with recertifying the fleet for flight. This could potentially be a large cost to the space tourism operator, especially the first time that it occurs. This could be in the neighborhood of $50 - $100 M.

Table XII: Failure Record for R = 0.999.

Failures	Frequency
0	568
1	342
2	90

This failure has a drastic effect on the economic viability of the program. In the initial case there was a 100% chance of obtaining a NPV greater than zero, in this case there is only a 55% certainty in reaching this value. That is a very low probability of success and it is unlikely that the project would be successful. The NPV resulting for this simulation is shown in Figure 12. This result tends to show a multi-modal tendency where both the failure and non-failure cases exhibit a normal distribution. The reason behind such a low chance of success is due to this multi-modal effect. The cases where there is a failure, either one or two failures, the NPV is less than zero, and this pulls the confidence level down because there is such a large percentage of the cases where the program isn't viable. The cause of this is that the number of passengers decreases so greatly in the cases where there is a failure that enough revenue can not be generated to offset the initial investment cost.

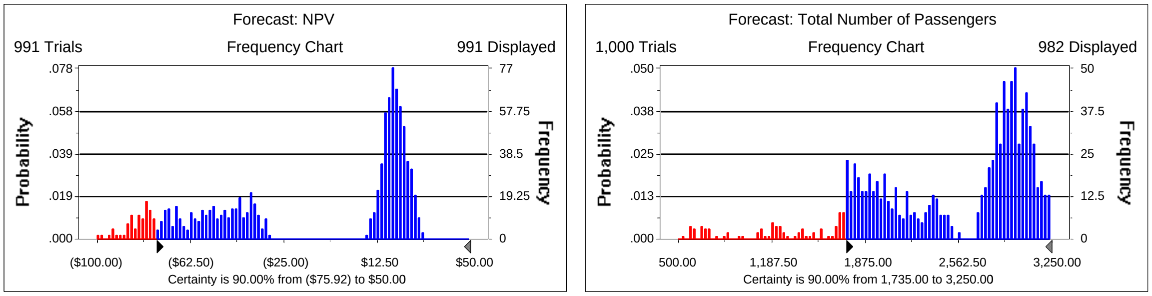


Figure 12: Virgin Galactic Results for R = 0.999 (NPV, Number Passengers).

The effect of the decrease in passengers is easily seen in Figure 13, in the cases where the program experiences a failure the total profit and ROI are negative. This signifies that the revenue generated was not enough to off set the total cost of the program. The 90% confidence values do not have much meaning in this case because there is such a discrepancy in the two cases. The importance of this study is that a vehicle failure is a very important factor to the economic viability of the program. This effect can not be simply ignored in the design of a successful project.

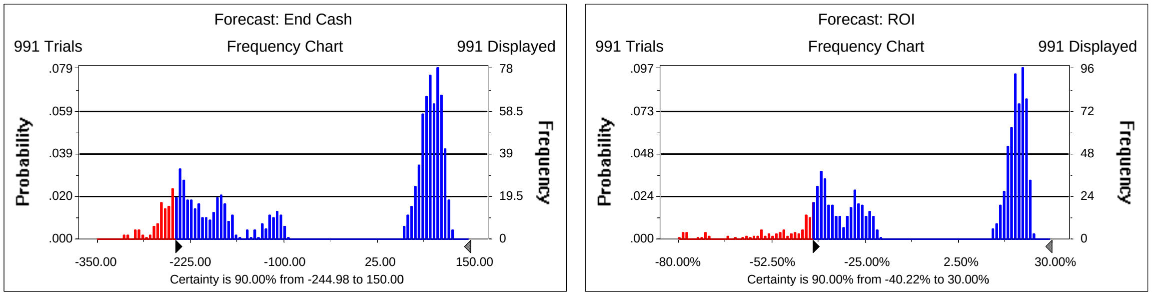


Figure 13: Virgin Galactic Results for R = 0.999 (ROI, Total Profit).

The cash flow analysis shown in Figure 14 is a representative look at the program life of the Virgin Galactic model. In this case there is a single failure that occurs in the second year of operations. The cash flow is very similar to Case 1 up through 2007, but with the failure in 2008 the program has a large expense that increases the debt to almost $100 M. This can not be recouped in the remains years of the program, especially at the decreased market demand that will be experienced in the following few years. It would take an additional five years of operations in order to re-coup the cost of this failure. It could be suggested that if a failure occurred Virgin Galactic would just end operations so that it didn't incur this recertification expense. Further study of the impact of this expense along with its magnitude should be conducted.

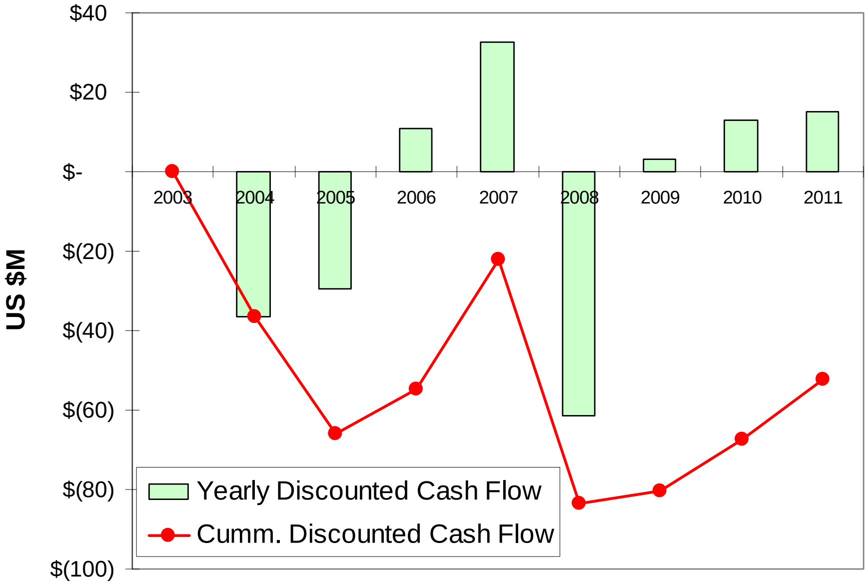


Figure 14: Virgin Galactic Cash Flow Analysis, 2009 Failure.

A summary of both cases are shown in Table XIII, note that the 90% confidence for Case 2 is only shown in order to provide a comparison to Case 1. The effect of a single vehicle failure for the Virgin Galactic model would eliminate any chance of the program becoming economically viable. The 0.999 reliability is very optimistic as a vehicle has never proven to have a flight reliability this high. The vehicle reliability will be very important in the design of a space tourism vehicle, and some time should be spent trying to understand the vehicle reliability and how it can be improved. It is very likely that Richard Branson would be willing to accept a program that wasn't profitable in order to be become the first operating space tourism company. It may be possible to re-design the Virgin Galactic model such that it has the capability of withstanding a vehicle failure.

Table XIII: Virgin Galactic Summary of Results (90% Confidence).

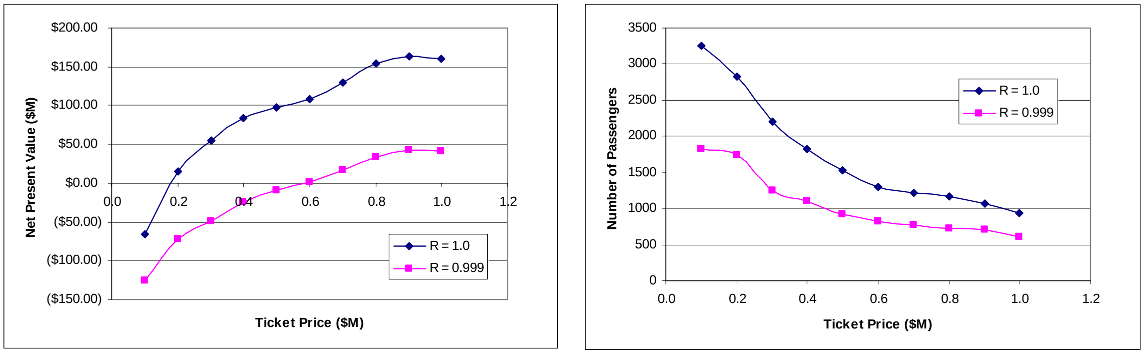
	R = 1.0	R = 0.999
Net Present Value ($M)	15.1	-75.9
Return on Investment (%)	16.9	-40.2
Ending Cash ($M)	81.6	-244.9
Number of Passengers	2,830	1,735

4.3 Virgin Galactic Study of Alternatives

This study will attempt to increase the robustness of the Virgin Galactic program such that it could withstand a possible failure and remain an economically viable program. In order to keep the baseline Virgin Galactic model, the passenger demand multiplier remained on the LMNoP market data so that the Virgin Galactic demand estimations could be used. Only the vehicle passenger capacity, ticket price and operating time frame were altered for this study. The initial investment of $125 M was also kept constant. The following set of trade studies should help establish trends in the market and provide some information on where a more optimized solution may exist.

4.3.1 Virgin Galactic Ticket Price Sweep, 5 passengers

The first trade study was to look at how the ticket price affected the outlook of the market. The ticket price was run from $0.1 – $1.0 M holding the other components of the Virgin Galactic model constant, except that the passenger demand was allowed to change according to the ticket price. The results for the NPV and the number of passengers as a function of the ticket price are shown in Figure 15, the $0.2 M point corresponds to the original Virgin Galactic model. The increase in ticket price, as expected, has a negative effect on the number of passengers willing to pay that price. There is a significant decrease in the total number of passengers, dropping from over 3,000 at a ticket price of $0.1 M to 600 for a $1.0 M ticket price. This actually has a very large positive effect on the NPV of the program. The case where the reliability was assumed to be 100% has a maximum NPV of over $150 M at a ticket price around $0.9 M, that is a 10x increase from the baseline Virgin Galactic model. The case where there is a 1/1000 chance of failure reaches a NPV greater than zero when the ticket price is increased above $0.6 M. This indicates that there is a program design that is robust enough to withstand a loss of vehicle.



* Calibrated for Virgin Galactic Market Model

Figure 15: Virgin Galactic Ticket Price Trade Study (5 Pax).

There are two important reasons why the NPV has such a positive correlation with an increase in the ticket price. The first and most important is that the increase in passenger revenue is larger then the decrease in passenger demand so the effect is a net increase in the total revenue generated each year. This tends to peak around a ticket price of $0.9 M where the percentage increase in ticket price becomes small. The second factor only affects the cases where reliability is added to the problem because a decrease in the number of passengers reduces the number of required flights which decreases the likelihood of a vehicle failure. This will force the case with reliability added to approach the 100% reliable case, this can be seen more clearly in Figure 18.

4.3.2 Virgin Galactic Ticket Price Sweep, 8 passengers

The second trade study was to look at how an eight passenger capacity vehicle would compare to that of the five passenger vehicle. The initial investment cost will remain $125 M, the effect of changing passenger capacity on the vehicle size and the total investment cost will be included in later studies. The eight passenger case is presented in Figure 16 and shows very similar results to that of the five passenger case. The NPV still peaks around $0.9 M, but the curves are shifted toward the left. This means that Case 2 now has a positive NPV for a ticket price greater then $0.4 M, $0.2 M less than that for the five passenger vehicles. That is a very large increase for only three additional passengers. The coupling of both an increase in the passenger capacity with the increase in ticket price allows the number of passengers for Case 2 to approach the 100 % reliability case at a much faster rate. This is again due to a decrease in the chance of failure associated with a decrease in the total number of flights.

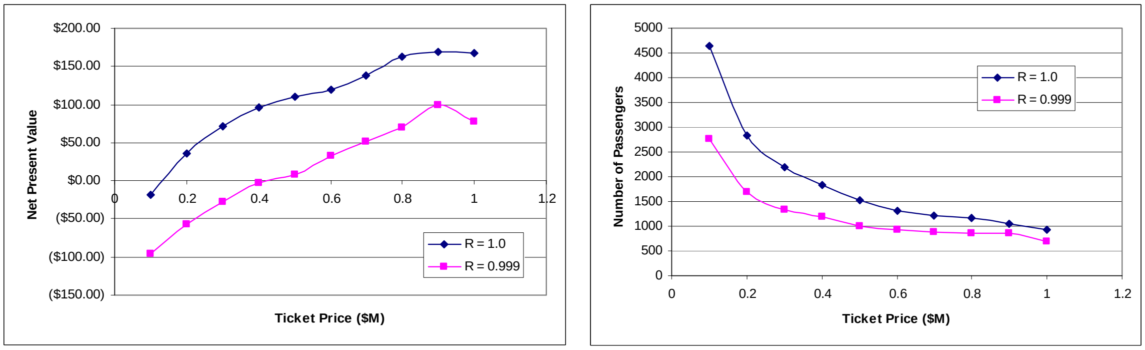


Figure 16: Virgin Galactic Ticket Price Trade Study (8 Pax).

4.3.3 Virgin Galactic Program Length Sweep, 5 passengers

The trade study was to look at how the operating length of the program would affect the economic viability. The ticket price was set at $0.2 M, the passenger capacity was set to five and the yearly passenger demand was set to match what was predicted by the Virgin Galactic model. The effect of increasing the program length from 4 – 14 years is shown in Figure 17.

The results of the 100% reliable case are as expected, since there are no losses associated with an increase in the length of the program the number of passengers and NPV both increase with an increase in operating years. This is the ideal case, it reality an increase in the number of years that the vehicle operate greatly increases the chance of failure. This is seen in Case 2 where there isn't a simple linear increase in the passenger demand. There is an unexpected maximum in the total number of passengers. At some point the increase in number of flights becomes high enough as to ensure a failure at some point in the program. At this point the total number of passengers drops off and remains relatively constant for any increase in program length. This could be offset by an increase in the passenger capacity and/or ticket price which would help to decrease the number of flights.

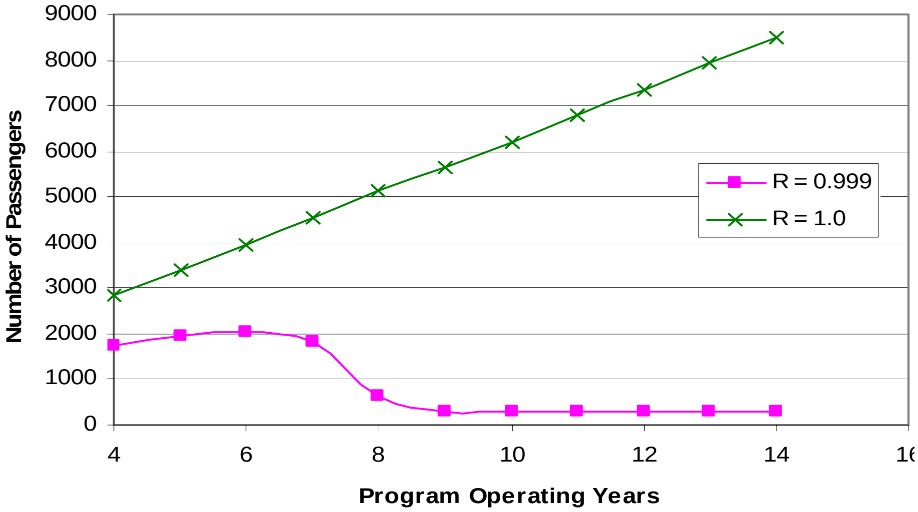


Figure 17: Virgin Galactic Operating Years Trade Study (5 Pax) 90% Confidence.

4.3.4 Virgin Galactic Program with Futron Data, Ticket Price Sweep

One of the major concerns with the Virgin Galactic market model is that it predicts a much larger passenger demand than any of the currently available models. It predicts 3x as many passengers as the LMNoP model at any given ticket price. Some of this was explained to be a result of the program only operating for five years, at which time there may or may not be another program available. However, it would be of interest to see how economically viable the Virgin Galactic model is if it used the LMNoP market demand model. These results are shown in Figure 18. The results of this study do not look very promising. There is only a small range of ticket prices that provide a positive NPV solution. Looking at the original Virgin Galactic ticket price (TP = $0.2 M) even the 100% reliable vehicle can not generate a positive NPV (NPV = -40 $M). The asymptotical trend of Case 2 is greatly exaggerated and nearly match the 100% reliable case for a ticket price greater then $0.6 M. For this low passenger demand case the vehicle's reliability doesn't have as large of an effect on the design of the vehicle program. By the time that the program has become viable the two curves overlap. These results should cause some concern for the viability of the Virgin Galactic model. If it doesn't get the passenger demand that it predicts, it will be very tough for the program to remain viable at the current ticket price.

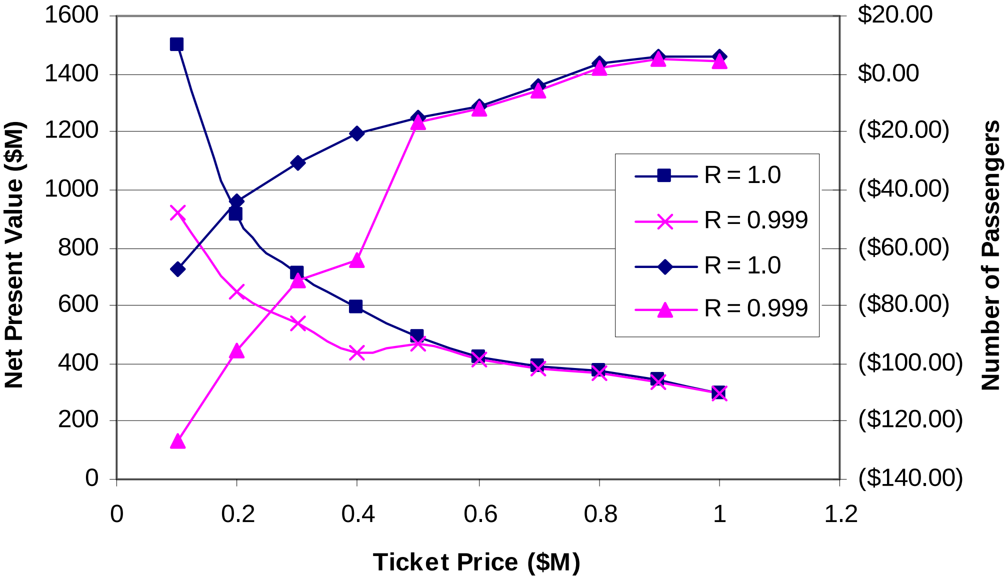


Figure 18: Virgin Galactic Ticket Price Trade Study (Futron Market Data).

These trade studies provided evidence that the Virgin Galactic model could be optimized to either improve upon the NPV or the total number of passengers that it services. The three lessons learned from these trade studies are the ticket price that could be charged, this will decrease the number of passengers, but at the same time greatly improve the economic viability, especially for the case where reliability is brought into the problem. The vehicle capacity seems to benefit the NPV of the program by increasing the revenue per flight without greatly increasing the recurring cost, this study was done assuming that an increase in the passenger capacity didn't increase the development cost. In actuality this would not be the case, for future studies the investment cost needs to be a function of the passenger capacity. The capacity also helps decrease the chance of failure because fewer flights are needed to meet the passenger demand. The program length had an unusual effect on the case where reliability was included. It would be interesting to see if an increase in the program length coupled with the other two factors could provide for a more optimized vehicle program. The Virgin Galactic model will be the first program to provide space access to the general public and in that it is truly revolutionary; however, it has much room for improvement is the overall design of the program. The next section will outline a study that could be used to guide the development of a more optimized and robust space tourism program.

5.0 Sub-Orbital Space Tourism Market Study

The sub-orbital space tourism market study will attempt to develop an understanding of what factors affect the design of a space tourism program. The factors under investigation are the same three from the trade studies done on the Virgin Galactic model, ticket price, passenger capacity, and program length in addition to fleet size. These factors were discussed in detail previously and are shown in Table X along with their specified ranges. The goal of the study will be to establish what combination of these factors optimizes the space tourism program. Recall that an optimized space tourism market considers two different philosophies, one is to maximize the net present value and the overall economic viability, and the second is to provide the maximum number of passengers access to space while maintaining a small profit. Both of these philosophies will be considered and a comparison of the two will be made to see what similarities and differences exist. Two studies that will be presented in this section. The first will be to determine what combination of ticket price, passenger capacity and fleet size will comprise the most optimized program while keeping the Virgin Galactic passenger demand model. This is being done so that a fair comparison can be made between the results of this study and the Virgin Galactic model. The standardized passenger model will provide a common platform to the compare the two results. The second study will differ from the first in that it will use the entire LMNoP model including the passenger demand curve, and the market expansion This will give the optimization more freedom as the length of the program will be included as a design variable. The hope here is that there is an optimal program length that balances the chance of failure with the total capability of the program.

The results of this study will be to help to guide the design of a new space tourism program. The results are not meant to be concrete, but rather as basic rules of thumb. It will be shown that there are many possible solutions to this problem, but these solutions tend to congregate in specific sections of the design space. It is these design sections that will be of interest in determining an optimally design program.

5.1 *Simulation Environment and Setup*

The ModelCenter® environment was use to simplify the interface between the optimizer and the LMNoP model. Crystal Ball was used for the Monte Carlo simulations from within the LMNoP model. This was done to help increase the speed of simulation, the less information that needs to be passed between models within ModelCenter the faster it will run. A snap shot of the ModelCenter environment is shown in Figure 19.

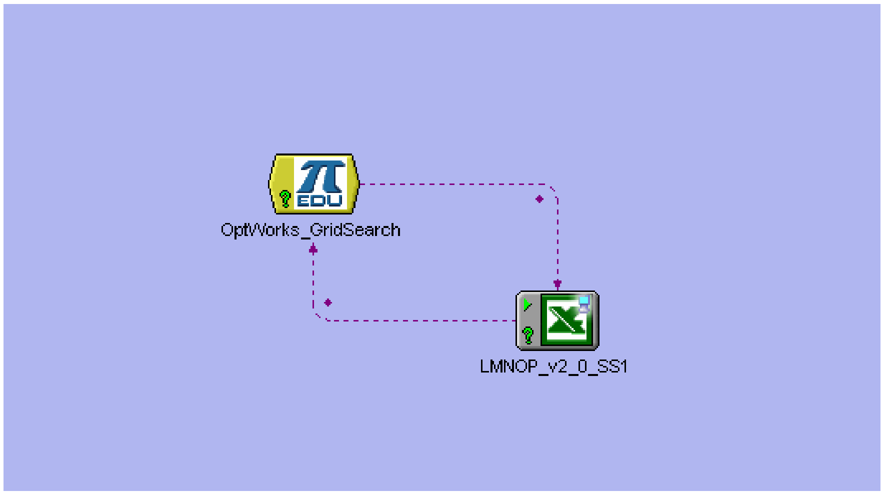


Figure 19: ModelCenter Optimization Environment

The Monte Carlo analysis is built into the LMNoP model and uses a VBA script to implement the simulation from within ModelCenter. Each simulation consists of 100 probabilistic simulations and 90% confidence value is taken from these results. An initial comparison was done between 100 and 1,000 simulations and only a small difference was seen in the 90% confidence value and so 100 simulation was used to help decrease the run time, each set of 100 simulations takes approximately 5 seconds to complete. The optimizers under consideration for this simulation were a Genetic Algorithm and a Full Factorial Grid Search. The Genetic Algorithm has the ability to handle integer design variables and in general can help to reduce the number of total function calls required for large problems. The main concern when using a Genetic Algorithm is that it uses random number generation when it moves through the design space and so is not guaranteed to find the optimal solution. In general the Genetic Algorithm should be run many times from different initial populations to confirm the results. Initially the Genetic Algorithm was used in this simulation, but after running the results multiple times it was clear that the optimizer would not be able to repeat the optimal value as it would change from one simulation to the next due to the of the stochastic nature of the simulation. There are a series of program configurations that are different in design but have very similar economic outputs. It was impossible to determine if the GA looked at all of these cases. Since the design space tended to have many similar solutions and the idea of this study was to find the target areas of the design space then it would be more useful to be able to see the entire design space so that a program designer would know where and where not to operate a program. Therefore it is decided to go with the Full Factorial Grid Search over the Genetic Algorithm. Since the probabilistic simulation only took a few seconds the Grid Search could be completed in a reasonable amount of time (< 1hr) and then the entire design space would be known. This would allow comparisons to be made between the different "optimal" designs and determine if certain factors were insensitive to changes in a particular design variable. An example of how the optimizers look at the different design spaces are provided in Figure 20 and Figure 21 , note just how many design points are very close to the actual optimal solution. The two lines shown in Figure 20 are the current and best ever solutions.

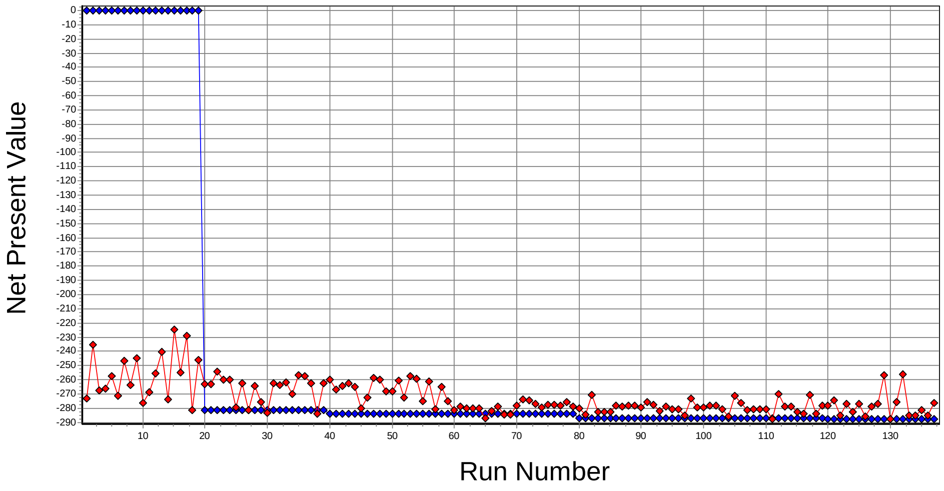


Figure 20: Space Tourism Design Space (Genetic Algorithm).

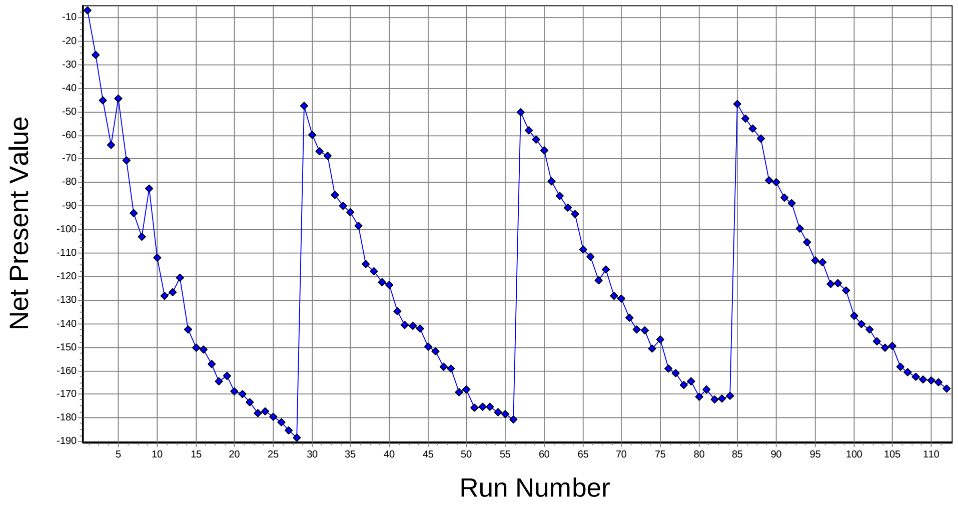


Figure 21: Space Tourism Design Space (Grid Search).

5.2 Market Optimization Using Virgin Galactic Market Model

5.2.1 Maximum Net Present Value Optimization (Virgin Galactic)

The maximum NPV solution was once again calculated for both a 100% reliable vehicle and for a vehicle with a 1/1000 chance of failure. The top four solutions for an R = 1.0 are shown in Table XIV. These four solutions have a NPV that is slightly greater than $186 M and total profit of about $480 M discounted to 2005 dollars. The total profit is the amount of money on hand at the end of the program after all expenses have been paid These are both much improved over the original Virgin Galactic model. There are two important trends that can be seen in these results. The first is that in order to optimize the NPV, the program would like to set the ticket price around $0.9 M. This is due to a greater increase in profit per flight than is lost due to the drop off in demand at the higher ticket prices. This effect tends to tail off at this ticket price, where the drop in demand becomes to great. The second trend to note is that the optimized solution wants to build only a single vehicle with a large passenger capacity. The program only needs a single vehicle to complete all of its missions (TAT = 14 days) especially for the small number of passengers expected. The greater passenger capacity provides greater revenue per flight without a proportional increase in the operating cost of the vehicle.

Table XIV: Maximize NPV, R = 1.0.

	Result 1	Result 2	Result 3	Result 4
Pass Capacity	10	9	9	8
Initial Ticket Price ($M)	0.9	0.85	0.9	1
Number Vehicles	1	1	1	1
Program Length (yr)	5	5	5	5
NPV ($M)	186	184	183	181
Number Passengers	1060	1134	1053	936
Total Profit ($M)	482	477	474	470

A very similar trend is seen in the case where a reliability of 0.999 is used, Table XV. The NPV is still around $180 M with a total profit of about $460 M. The differences here in these top results are likely due to the variations in the Monte Carlo simulations and not actual different optimal design points. This case tends to approach the 100% reliable case discussed above because at the high ticket price such that the market demand has decreased to a level where the chance of failure is very small and the design is no longer dependent on the reliability of the vehicle.

Table XV: Maximize NPV, R = 0.999.

	Result 1	Result 2	Result 3	Result 4
Pass Capacity	10	10	8	9
Initial Ticket Price ($M)	1	0.85	0.9	1
Number Vehicles	1	1	1	1
Program Length (yr)	5	5	5	5
NPV ($M)	180	178	177	173
Number Passengers	930	1090	1032	612
Total Profit ($M)	467	461	458	448

A comparison between Result 1 and the Virgin Galactic model is shown in Figure 22, the bar chart on the left includes the design variables while the chart on the right has the economic outputs (NPV, Number of Passengers, and Total Profit). There is a very large increase in both the NPV going from $15.7 M to $186 M and the total profit going from $82 M to $482 M. These are simply accomplished by increasing the ticket price, increasing the fleet size and the passenger capacity of the vehicle. These are design changes that could easily be implemented into a new program, so it begs the question as to why the program was designed so differently. This questioned will be answered in the next study.

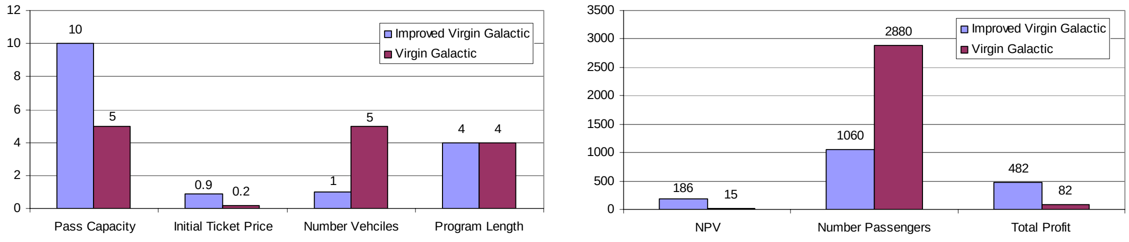


Figure 22: Virgin Galactic Demand Model Comparison (Max NPV).

5.2.2 Maximum Number of Passenger Optimization (Virgin Galactic)

The second study in this section looks at how to optimize a space tourism program in order to maximum the actual number of passengers. This goes along with the second philosophy, that the goal of a space tourism program is to provide a service to humanity and creating an economically viable program is only a minimum requirement and not the main objective function. The first of these results, the case where the reliability is 100%, is provided in Table XVI. These results are vastly different than the ones seen for the maximum NPV cases discussed above. The major difference to note is that the ticket price has dropped dramatically as would be expected knowing the correlation of ticket price and market demand. The ticket price however didn't reach the minimum allowable ticket price of $0.1 M because at this price the program isn't economically viable and so even though the number of passengers was greater, a program couldn't operate in this region and so these cases were discarded. The $0.2 M was the minimum ticket price for which a NPV of greater than zero could be obtained. The passenger capacity still tends to be high because this allows more revenue to be generated for each, this allows for a lower ticket price to be charged and a corresponding increase in the passenger demand. The fleet size is larger than the previous case because a single vehicle does not have enough capability, even at the high capacities. The optimal number of passengers requires at least three vehicles (9 Passengers) to meet the 2,850 passenger requirement over a five year program with an assumed turn around time of

14 days. These design variables correspond to a NPV between \$25 – \$40 M and a total profit of \$100 M.

Table XVI: Maximize Number of Passengers, R = 1.0.

	Result 1	Result 2	Result 3	Result 4
Pass Capacity	7	9	9	10
Initial Ticket Price (\$M)	0.2	0.2	0.2	0.2
Number Vehicles	4	3	5	3
Program Length (yr)	5	5	5	5
NPV (\$M)	26	38	28	39
Number Passengers	2856	2844	2844	2840
Total Profit (\$M)	98	127	109	130

In this optimization problem the solution is a function of the vehicle reliability and some differences will exist in the program design variables between these two scenarios. The reliability plays an important factor in this solution because the number of passengers is directly related to the chance of vehicle failure. A high chance of failure will decrease the economic viability of the program because of the large cost associated with the loss of a vehicle along with the decrease in demand that would be seen following such a failure. The solution counters this increased chance of failure by increasing the ticket price and decreasing the number of passengers until the chance of failure decreases and the NPV becomes greater than zero. This effect is shown in Figure 23 where the actual maximum number of passengers occurs at a ticket price of 0.2 \$M, but the cutoff for an economically viable solution is at a ticket price of 0.35 \$M. A ticket price of 0.2 \$M corresponds to the value obtained in 100 % reliable solutions because the NPV cutoff for this solution is less then \$0.2 M and so the solution can reach this peak.

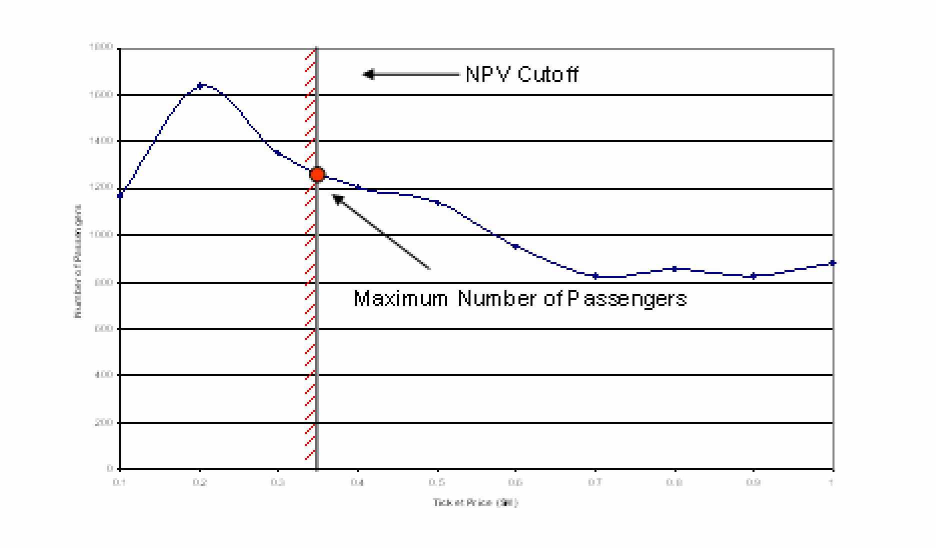


Figure 23: Maximum Passenger Ticket Price Cutoff.

The top four solutions are shown in Table XVII. All of these solutions have a low NPV around $10 M and total profit of about $50 M. If the resolution of the problem was increased the solution would drive down the ticket price until the NPV = 0 or whatever minimum level was set. The results are a ticket price of about $0.35 M and a fleet size of two vehicles, which is capable of providing flights for over 1,300 passengers while maintaining an economically viable program.

Table XVII: Maximize Number of Passengers, R = 0.999.

	Result 1	**Result 2**	**Result 3**	**Result 4**
Pass Capacity	9	10	8	9
Initial Ticket Price ($M)	0.35	0.4	0.4	0.45
Number Vehicles	2	2	2	3
Program Length (yr)	5	5	5	5
NPV ($M)	8	17	15	12
Number Passengers	1,377	1,260	1,112	1,107
Total Profit ($M)	61	37	56	41

A comparison of the program design variables are provide in Figure 24. The results are similar for both cases with the first case having a lower ticket price, about 50% less, and a slightly large fleet size.

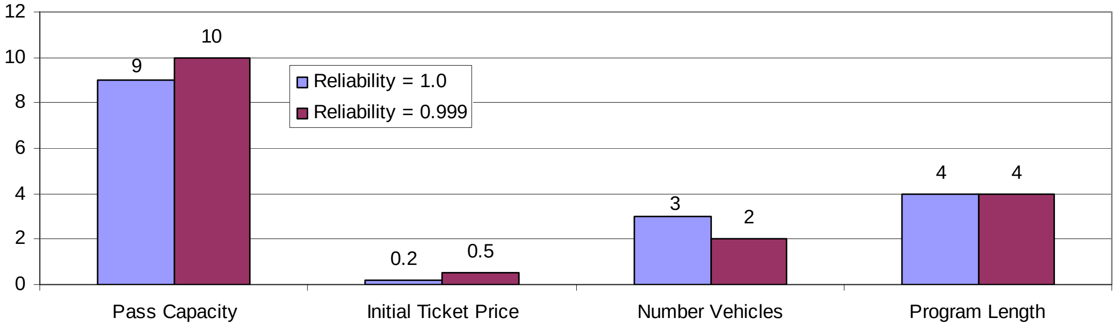


Figure 24: Maximum Passenger Reliability Effect Comparison.

A comparison is made between this study and the results of the Virgin Galactic model. The interesting result here is that the solution for the maximum number of passengers is very similar to the Virgin Galactic model. In actuality the differences between the two solutions are within the noise of the LMNoP model. It is very interesting that the Virgin Galactic model so closely matches the maximum passenger philosophy. If you assume that the Virgin Galactic program is modeled to provide the maximum number of passengers, then this provides some confidence in the results of the LMNoP model. This assumption is likely to be true as the Virgin Galactic company is only one of hundreds of companies in the Virgin Empire and providing space tourism flights will bring a lot of publicity to the overall company.

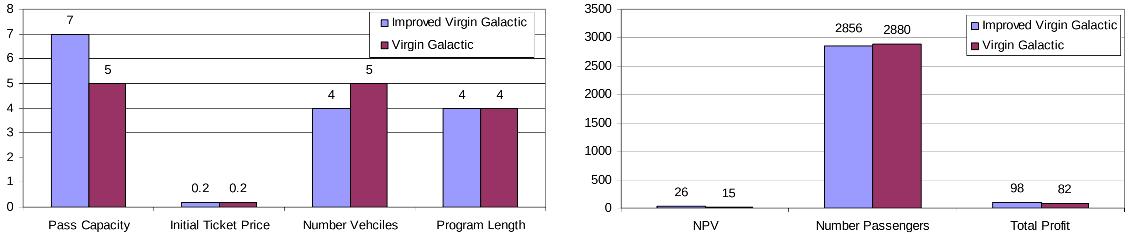


Figure 25: Virgin Galactic Demand Model Comparison (Max Passengers).

5.3 Market Optimization Using LMNoP Market Model

The second space tourism market study will be similar to the first study in that it will look for an optimal program design for both a maximum NPV and a maximum number of passengers. The differences are that it will add the program length as an additional design variable. This variable establishes the number of years the program will provide space tourism flights. In addition to this the market demand model will use the results of the Futron market study that is currently built within the LMNoP model instead of the Virgin Galactic passenger demand model. This model predicts a much lower number of passengers then the Virgin Galactic model, but it is not restricted to a single program length. This demand curve is representative of how the market would behave over a longer period of time and will provide a more robust solution to the optimal program. The results from this study will be used to characterize the sub-orbital space tourism design space and produce a set of guideline to aid in the design of future programs.

5.3.1 Maximum Net Present Value Optimization (Futron)

The results for the top four design points are shown in Table XVIII. These results are similar to those seen in the Virgin Galactic study. The ticket price is set to just under $0.9 M, this is a recurring trend that is seen in each of the three studies preformed. The NPV of the program seems to peak at these higher ticket prices. This limits the number of passengers to around 70/year for 12 years. This limited number of passengers requires only a single vehicle with a passenger capacity of nine. This design results in a program NPV of $50 M and total profit of $274 M.

Table XVIII: Maximize NPV, R = 1.0.

	Result 1	**Result 2**	**Result 3**	**Result 4**
Pass Capacity	9	10	8	7
Initial Ticket Price ($M)	0.88	0.88	0.84	0.88
Number Vehicles	1	1	1	1
Program Length (yr)	12	12	12	12
NPV ($M)	53.0	52.9	52.0	51.8
Number Passengers	819	830	864	819
Total Profit ($M)	274	276	268	266

When reliability is included in the problem the economic return drop slightly as there is a decrease in the average number of passengers over the 100 probabilistic simulations. The optimal design points are basically the same, due to a decrease in flights, so that this case approaches the 100% reliable solution shown above. The only difference is that the program length tends to be slightly lower in this case. This is because there is a peak in the NPV where the number of passengers flown and the chance of failure balance such that that total chance of failure is balanced. The NPV will decrease for lower ticket prices and longer operating years. The results of this study are shown in Table XIX. The NPV obtained is slightly lower then $50 M with a total program profit of $240 M.

Table XIX: Maximize NPV, R = 0.999.

	Result 1	**Result 2**	**Result 3**	**Result 4**
Pass Capacity	9	7	8	10
Initial Ticket Price ($M)	0.88	1	1	0.84
Number Vehicles	1	1	1	1
Program Length (yr)	11	11	12	11
NPV ($M)	48.6	47.5	48.5	47.3
Number Passengers	747	637	688	780
Total Profit ($M)	242	237	256	239

5.4 Maximum Number of Passenger Optimization (Futron)

The final sub-orbital program study was to use the LMNoP market curves to determine the optimal program to maximize the number of passengers. In this case, where the reliability is assumed to be 100%, the ticket price is set to $0.3 M. This is higher than what was found for the Virgin Galactic model because the minimum ticket price to meet the NPV >0 requirement is slightly higher for this smaller market. This results in about 140 passengers/year and again only a single vehicle is required to meet this demand. The NPV is very low for this case, almost zero, and puts the minimum ticket price for a NPV > 0 at $0.3 M. This is the maximum number of passengers that can be carried while still remaining an economically viable program.

Table XX: Maximize Number of Passengers, R = 1.0.

	Result 1	**Result 2**	**Result 3**	**Result 4**
Pass Capacity	8	9	7	10
Initial Ticket Price ($M)	0.3	0.3	0.3	0.3
Number Vehicles	1	1	1	1
Program Length (yr)	12	12	12	12
NPV ($M)	0.0	0.8	1.7	1.6
Number Passengers	1,664	1,656	1,652	1,650
Total Profit ($M)	46.9	52.3	37.0	56.5

In the case where reliability is included in the problem there is a major jump in the ticket price so that the flight rate is limited and the chance of failure remains low. The ticket price plays the same game and moves to the lowest value that will still provide a positive NPV, these results are shown in Table XXI. This decreases the number of passengers to about 100/year. This results in about $45 M in revenue per year and a total program revenue of $540 M. This still allows the program to have a NPV slightly greater than zero and total profit at the end of the program of about 55 $M. In order to meet the flight rate the program only needs a single vehicle, but still chooses to build 2 – 3 vehicles. This is because of the way that LMNoP handles the loss of a vehicle. If a vehicle is lost the program does not rebuild a new vehicles, it assumes that all of the vehicles are purchased at the beginning of the program. When a vehicle is lost it decreases the size of the fleet and the program continues. So if the fleet size is only a single vehicle and that vehicle is lost then the program ends and the total passenger demand is likely to be very low for that case. Therefore the program will tend to build multiple vehicles at the start of the program so that if a failure occurs the program can continue just with a reduced capability.

Table XXI: Maximize Number of Passengers, R = 0.999

	Case 1	Case 2	Case 3	Case 4
Pass Capacity	10	9	10	10
Initial Ticket Price ($M)	0.45	0.5	0.45	0.4
Number Vehicles	3	2	2	1
Program Length (yr)	12	12	11	10
NPV ($M)	1.2	13.4	5.6	7.6
Number Passengers	1,220	1,125	1,120	1,030
Total Profit ($M)	54	121	91	78

5.5 Philosophy Optimization Comparison

This space tourism program study set out to look at the optimized solution for two philosophies considered to be important in space tourism. Should a space tourism program be designed to maximize the economic return or should it provide a service to humanity? This study isn't going to go into the details as to which of these is better, but rather attempt to point out some commonality and the major differences between the two and leave the decision as to which one to implement up to the space tourism industry.

A comparison of the two results for the R = 0.999 case are provided in Figure 26. The chart to the left displays the design variables and the chart to the right displays some interesting economic outputs. These charts show some of the fundamental differences in the design of these two programs. The maximum NPV case has the capability to generate about 5 times the profit of the maximum passenger case, but at the same time the first case can only provide about half of the flights as the second case. This was the goal of the two cases and you can see the drastically different solution each was able to obtain. The design points for these two cases differ in only 2 of the 4 categories, the ticket price and the fleet size. The program length and passenger capacity are generally set to there maximum values for both cases as these two variables only affect the profitability of every flight and should be maximized for any space tourism program.

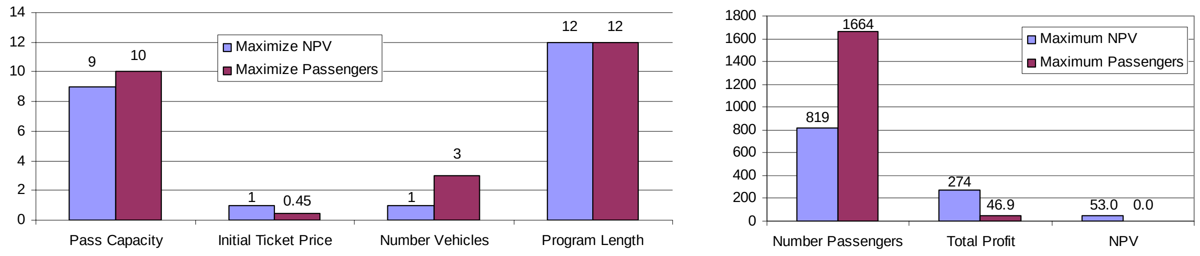


Figure 26: LMNoP Optimal Solution Comparison.

The ticket price for the maximum NPV case is about twice that of the maximum passenger case, this makes sense because the second case wants to attract as many passengers as possible and this can be done by providing the lowest possible price. The first case also wants to minimize the size of the fleet because this reduces the size of the initial investment and as long as it doesn't greatly reduce the program's capability it will increase the NPV. The second case needs a larger fleet size to account for both a greater demand and a higher chance of failure. Both of these designs have their place in a space tourism market. The first case is what would be expect for an initial space tourism program as it charges the highest price to those who want to be the first space tourist. In a competitive market it would be very difficult to implement this type of a program because if such a high ticket price was charged then it would be very easy for a competitor to move in and offer a lower price. This would cause the market price to drop until the competing companies reached their minimum ticket price at which they could remain an economically viable space tourism provider. This would likely occur at a similar level and it would be expected that the competing companies would receive similar market share and offer similar ticket prices. This is similar to the maximization of the number of passenger scenario. These two cases therefore operate at two of the most typical points within any economic market. Case 1 can be used when 100% of the market is captured and people are forced/willing to pay a higher price, and Case 2 is used in a competitive market where obtaining the largest market share is important and therefore a company would likely offer the lowest possible price.

5.6 Space Tourism Optimal Design Guide

The results of this study are presented here as a guide for designing a new space tourism program. The actual results will be vehicle specific and depend on the current market factors, but these results should still hold as a general solution to the design of a space tourism program.

Maximum Net Present Value

Design Variables

- Passenger Capacity – The passenger capacity of each vehicle should be as high as can be reasonable designed. A capacity of 10 should provide a reasonable target value.
- Fleet Size – The fleet size should be minimized to meet the available demand, this will be 1 – 2 vehicles in most cases.
- Program Length – The program should be operated for periods longer than 10 years, and as long as the vehicles are maintained and the demand is there, the business could easily be operated for longer periods. The risk a failure increases at the length of operation increases.
- Ticket Price – The optimal setting of the ticket price would be around $0.9 M, this would assume that there is 100% market capture.

Expected Results

- The Net Present Value should be much great than zero, values greater than $50 M for a discount rate of 17.5% would not be unexpected.
- The annual number of passengers will be low; the tickets would only be available to the upper class. Expect a 100% market capture of less than 100 passengers per year.

Maximum Number of Passengers

Design Variables

- Passenger Capacity – The passenger capacity of each vehicle should be as high as can be reasonably designed. A capacity of 10 should provide a reasonable target value.
- Fleet Size – In general the fleet size would need be greater than a single vehicle, and will depend on the percentage of the market captured. A good starting point would be enough vehicles to meet the annual flight requirements + 1.
- Program Length – The program should be operated for periods longer then 10 years, and as long as the vehicles are maintained and the demand is there, the business could easily be operated for longer periods. The risk of failure will be decreased by the increase in the fleet size.
- Ticket Price – The ticket price should be set as low as possible and still maintain an economically viable solution. This would tend to be around \$0.4 – \$0.5 M.

Expected Results

- The number of passengers will be very high; the largest amount of people should be able to afford a ticket. Expect a 100% market capture of 150 passengers/year.
- The Net Present Value should be very close if not equal to zero, as profits and revenue will be small.

6.0 Orbital Space Tourism Market Study

The orbital space tourism study will look at viability of three different space tourism markets. This study will include a single-orbit, a multi-orbits and orbital docking mission comparison. An orbital vehicle is the logical next step in the development of the space tourism industry. This however is not an easy step and requires a much larger investment of time and money than for the development of a sub-orbital vehicles. The benefit is that the return on investment is much greater making this industry very appealing if the development hurdle can be overcome. A description of the three missions are outlined below:

Single-Orbit Mission

- Simpler design and development, no orbital insertion
- Shorter mission decreases operating cost, less ground monitoring
- Worse passenger experience for shorter mission, < 1hr space flight
- Still requires a large development cost

Multi-orbit Mission

- Longer mission provides better view and experience
- Passengers have time to adjust to orbital environment
- Additional ECLSS systems adds complexity
- Insertion velocity increases system size and complexity

Orbital Docking Mission

- Long duration stay in an orbiting space hotel, possible weekly stay
- Higher ticket prices can be expected
- Docking capability adds weight and complexity
- Launch operations greatly increase required ground monitoring

A simple model of each of these vehicles was developed where the required delta-V, number of passengers, and time of flight could be input and the weight of the vehicles could be estimated. A curve fit was developed for each of the three missions as a function of passenger capacity. The corresponding weights for a five passenger capacity vehicle are shown in Figure 27. The multi-orbits and orbital docking missions are significantly higher than the one-orbit mission as they require a larger propulsion system and a longer operating environmental control and life support system (ECLSS).

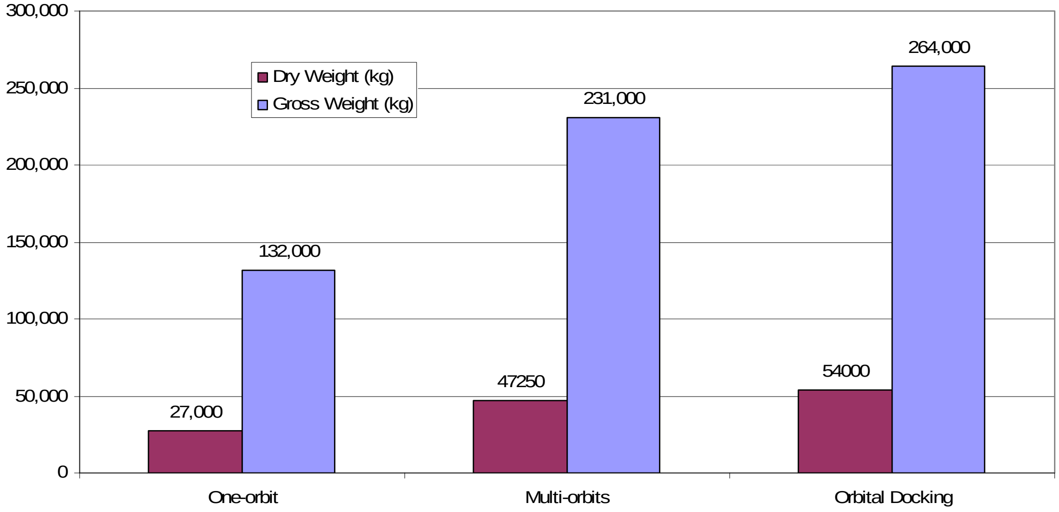


Figure 27: Orbital Vehicle Weight Comparison (kg), 5 passengers, 1 Crew

These models are fairly simple in nature and therefore serve as a comparison of the different missions and not as a detailed design of the vehicle. These provide for a first order analysis only, and are used to obtain an estimate on the vehicle development cost.

The development and production cost for this vehicle are provided in Figure 28. These costs were derived from the orbital TRANSCOST model built into LMNoP. The orbital insertion missions require a larger investment cost then the single orbit mission as expected, but all three require a significantly larger investment then the sub-orbital case discussed previously. The acquisition of such a high initial investment funds is one of the major obstacles that must be overcome in order for the orbital space tourism industry to exist in the future. It will be difficult to secure funds of such magnitude due to the high risk involved in the development of such a vehicle.

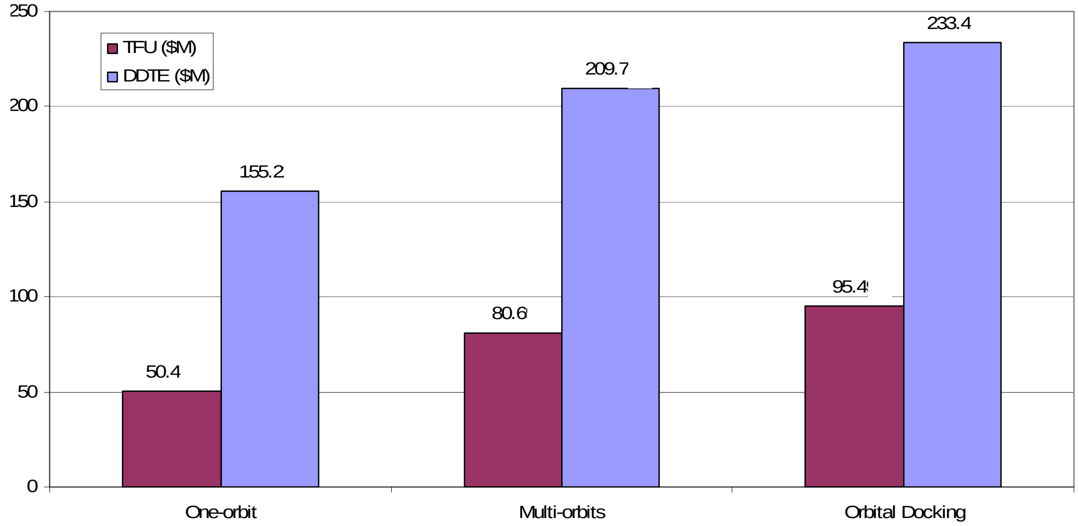


Figure 28: Orbital Vehicle Development Cost ($M) , 5 passengers, 1 Crew

The operational costs are also much greater for an orbital mission. The vehicles must endure a much harsher environment during the ascent and landing phase. This leads to much more intensive ground operations and a corresponding increase in the vehicle turn around time. There is also an increase in the mission operations cost as the vehicle is in flight for a much greater amount of time. In the Sub-orbital case the vehicle is in a space environment for only 10 – 15 minutes. The orbital missions extend this time to as much as 90 minutes for the single orbit, 6 – 10 hours of a multi-orbits mission and 7 days for the orbital docking mission. This increase in the mission time requires more ground monitoring operations, especially in the orbital docking case. It is likely that a ground crew will need to monitor the vehicles 24 hrs a day while the passengers are in the space hotel. This cost accounts for the major increase that seen in Figure 29 between the multi-orbits and the orbital docking missions. This additional launch cost will greatly reduce the economic viability of the orbital docking mission as the profit/launch will not be high enough to re-coupe the initial investment cost. The fixed cost are provided per launch with at total of four launches per year.

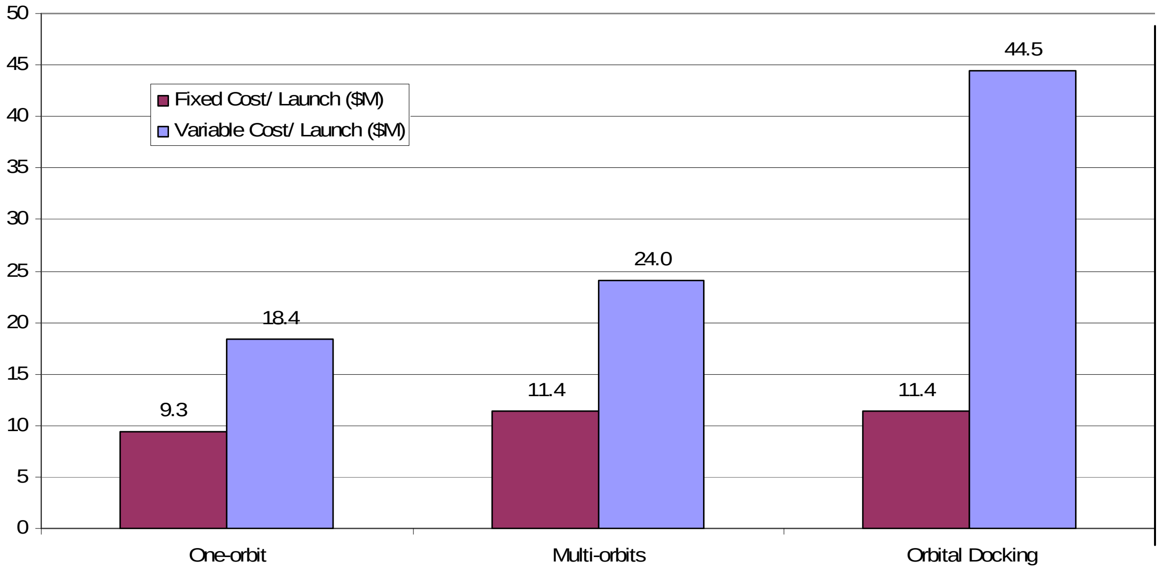


Figure 29: Orbital Vehicle Operational Cost Comparison ($M) , 5 passengers, 1 Crew

The orbital space tourism study will evaluate which of these missions is the most economically viable and then present the optimal solution to this mission in terms of ticket price, fleet size, program length, and passenger capacity. The optimization will be to maximize the NPV of the program and not look at the total case of maximizing the number of passengers. It is assumed if the funds for this project can be secured the investor(s) will want a large return on his investment and not worry about the total number of passengers. The risks involved in the development of this mission are not taken into account and it is assumed that the vehicles within the design space can be developed and ready for service by 2014. The results of this study will verify the economic viability of the orbital space tourism industry as compared the sub-orbital market that will begin operations in 2007.

6.1 Orbital Space Tourism Market Study

The results of the sub-orbital Market study showed that the optimized NPV solution was mostly dependent on the ticket price, and that high ticket price solutions generally resulted in less fights and a higher NPV. The ticket price will be used to compare the economic viability of the three missions here as well. The results of this trade study, for a ticket price between $1 – $15 M, are shown in Figure 30 and a 100% reliability. These three curves exhibit the same trend with economic viability unobtainable at the low ticket prices. The curve slowly increase to a peak around a $12 M ticket price for all three missions.

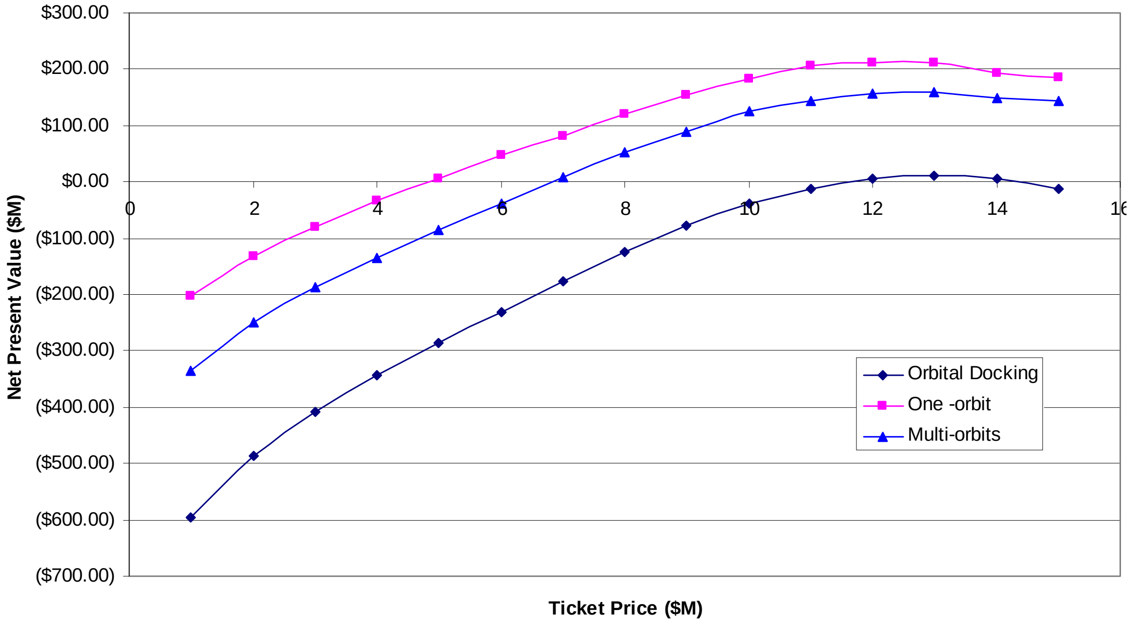


Figure 30: Orbital Missions Ticket Price Trade Study.

The unexpected result of this study is that the orbital docking mission is only viable for a small region of ticket price, while the other two missions have a much wider viable design space. The NPV for this region is so small as to basically eliminate it from consideration. This can be explained by the fact that the recurring cost for this mission is so much higher than the other two. The required monitoring increases the cost such that profit for each flight can not make back the initial investment cost. Even if this mission showed a positive NPV it doesn't provide that much of an increase in demand to justify the increased initial development and risk involved with developing a vehicle capable of docking with an orbiting space hotel.

The other two curves are very similar and show much more promising possibilities. The single orbit mission actually looks to be the best because its initial investment and operating cost are much less, and the additional passengers that the multi-orbits mission gets aren't enough to offset the difference. However, the single orbit mission is unlikely to be very enjoyable for most space tourism passengers as it can take a while to adjust to a zero gravity environment. Therefore it is suggested that the multi-orbit missions provides the most viable economic solution to the orbital space tourism problem. This mission will be examined further in the following section.

6.2 Orbital Space Tourism Program Optimization

The optimization of the ticket price was shown in Figure 31 and was determined to be around $12 M/Launch. This is the same results as seen in the sub-orbital study. There is a peak in the ticket price for a maximum NPV that occurs at the ticket price were the loss in passengers becomes too great to be overcome by the marginal increase in revenue. This limits the number of passengers/year to 32 for a 50% market capture.

The passenger capacity also factors largely into the design of the vehicle as higher passenger requirements increase the cost and complexity of the vehicle design. The vehicle's reliability will be brought back into the problem at this point because the passenger capacity is highly dependent on the chance of failure. The results for a 100% and 0.995 reliability are shown in Figure 31, the program length is set to 10 years, the ticket price is set to $12 M, and the fleet size is set to 1. The 100% case has a peak NPV for a passenger capacity between 4 – 6 passengers. This is the minimum passenger capacity that can meet the passenger demand without increasing the fleet size above a single vehicle. An additional vehicle would only decrease the NPV, and would not provide any additional capability. When the reliability is added to the mission the passenger capacity shifts to a much higher capacity of passengers as it wants to limit the number of flights. This can bee seen in Figure 31 as the results that include reliability tend to approach the 100% reliable results as the passenger capacity increases resulting in a decrease in the number of flights . It is better to spend more money up front and design a larger vehicle than it is to risk a failure occurring at some point in the program. These two curves provide an upper and lower bound on the vehicle passenger capacity. The more reliable the vehicle is the lower the passenger capacity can be.

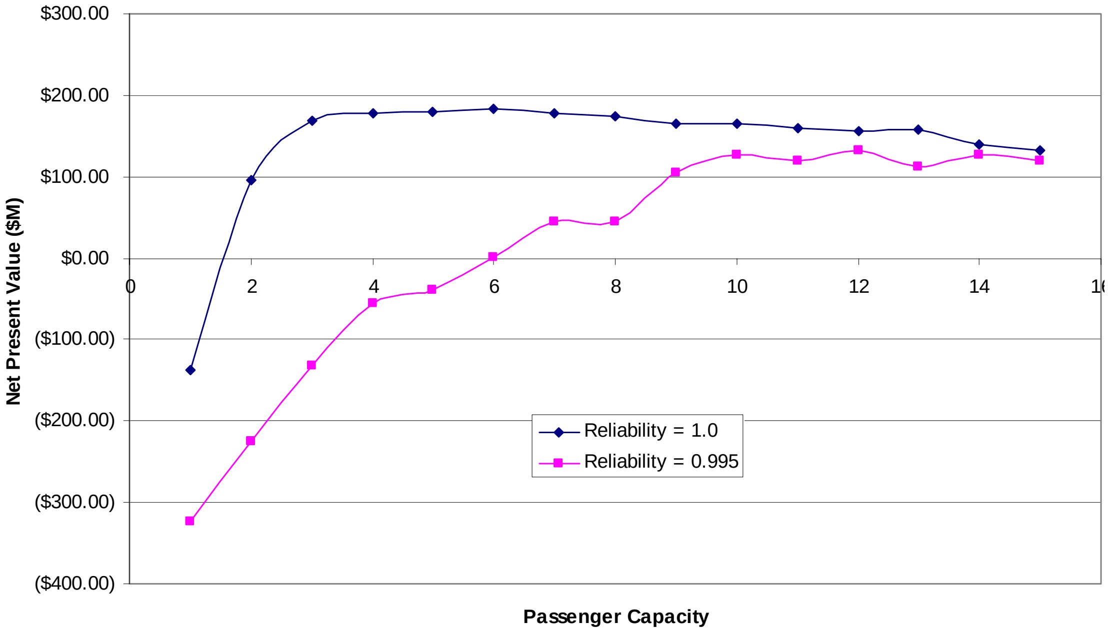


Figure 31: Orbital Missions Passenger Capacity Trade Study.

The program length is also an important variable in the design of the overall program because the longer the vehicle operates the more revenue it can generate and the greater the return on investment. This is true for the case where the vehicle doesn't experience a chance of failure, however in the case where there is a chance of vehicle failure there is maximum number of years the vehicles can operate before the chance of failure increase such that a failure occurs in almost every simulation and a greater NPV can not be achieved. Therefore there is a balance between the number of years that the vehicle brings in revenue and the chance of failure that occurs for an increase in the number of flights. In this case this optimal program length is 10 years, after that the chance of a failure occurring is too high for the program to be economically viable. These results can be seen in Figure 32.

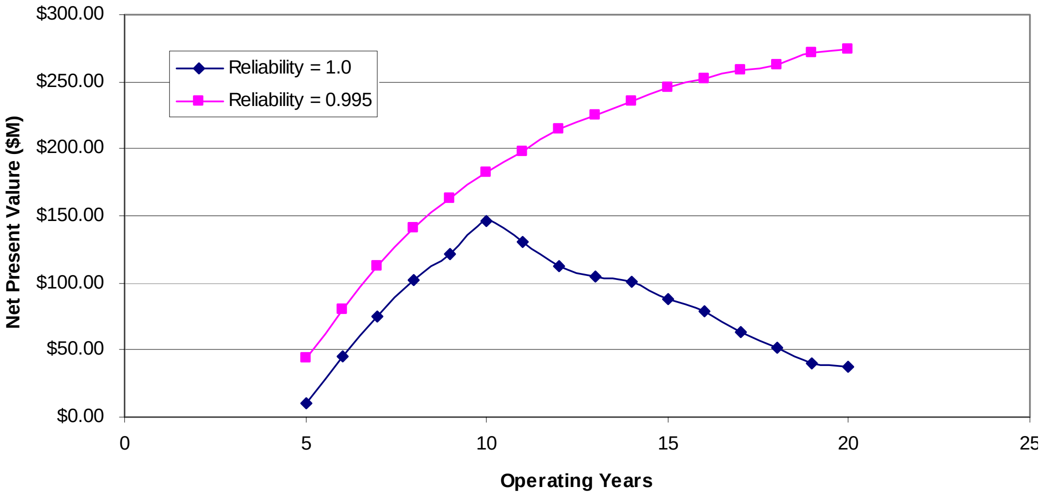


Figure 32: Orbital Missions Operating Trade Study.

The final variable of interest was the vehicle fleet size. The passenger demand for a orbital-space program is not very large, the profit is made from price not volume, and so a large fleet size is not required. The results run above were all for a single vehicle because that is all that is required to meet the demand, assuming a 30-day turn around time. Increasing the number of vehicles only decreases the NPV because the additional vehicles don't add any additional capability. Even in the case with reliability the NPV is maximized for single vehicle. In reality additional vehicles may be needed to account for unexpected problems that may cause a delay in a vehicle launch. Additional vehicles will help to guarantee that the launch schedule remains intact.

The optimized program for an orbital space tourism mission is given by the following

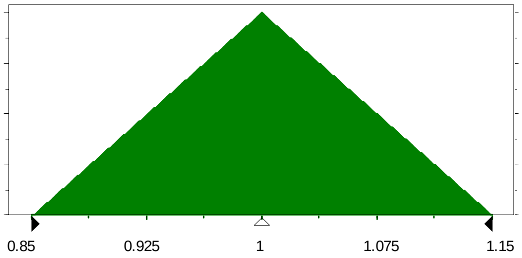
- Mission: Multi-orbits
- Ticket Price: $12 M
- Passenger Capacity: Depends on reliability (6-10 passengers)
- Program Length: 10 years
- Fleet Size: 1 vehicle

7.0 Conclusion – Viability of Future Space Tourism Market

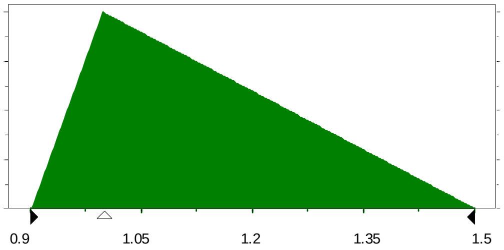
The space tourism study presented here utilized an updated version of the economic analysis tool LMNoP to conduct a series of studies to determine the economic viability of the space tourism market. The updated version of LMNoP included an update of the passenger demand market model derived from the market data collected by the Futron Corporation. This economic analysis determined that the Virgin Galactic model is an economically viable market in its current form as long as a failure doesn't occur during the life of the program, if one does occur the recovery expresses are too great to overcome. It was also determined that the Virgin Galactic model is likely operating under the idea that the goal of space tourism industry is to provide as many flights as possible and making a profit is secondary. The Virgin Galactic model showed very similar results to the sub-orbital program optimized for maximum total number of passengers, where the ticket price should be set as low as possible such that the program can still keep a positive NPV. The study also found that the optimal program to maximize the economic viability of a space tourism company is to set the ticket price slightly less then $1 M, have a high passenger capacity (10 Passengers/flight) and to operate only a single vehicle. This will provide the largest NPV, but at the same time many less passengers will be able to afford a ride. The orbital space tourism market is most likely to succeed when a multi-orbits mission is employed. The program again wants to charge a very high ticket price, $12 M and operate only a single vehicle for 10 year period. The passenger capacity is highly dependent on the reliability of the vehicle and should be kept in the range of 6 – 10 passengers/Vehicle.

The results of this study have concluded that the space tourism industry is a very viable economic market and has great possibilities for the future. With the successful launch of SpaceShipOne and the formation of Virgin Galactic, the next generation in space adventure has begun.

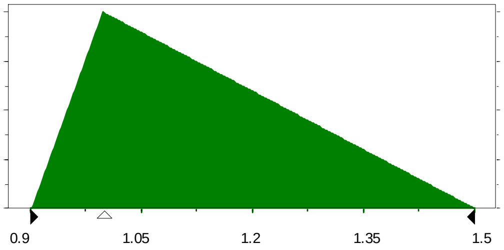
Appendix A: Monet Carlo Triangular Distributions



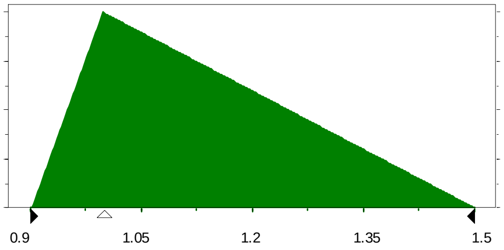
Baseline Passenger Demand



Development Cost



Production Cost



Operating Cost

Appendix B: Tourism Vehicle Model Orbital Example

First Stage –

			Level 2	Level 1
Wing Group				11,298
Tail Group				5,491
Body Group				48,737
	Primary Structure		34,686.113	
	Seondary Sructure		1,020.180	
	Crew Cabin		0.000	
	Body Flap		0.000	
	Thrust Structure		2,068.562	
	LOX Tank		4,197.435	
	LH2 Tank		6,765.152	
Thermal Protection				0
Landing Gear				10,676
Main Propulsion				18,604
RCS Propulsion				0
OMS Propulsion				0
Primary Power				991
Electrical Conversion & Dist.				7,710
Hydraulic System				0
System Control Actuation				1,558
Avionics				1,750
Envronmental Control				1,326
Personal Equipment				0
Dry Weight Margin				16,221
Dry Weight				**124,362**
Crew and Gear				0
Payload Provisions				0
Cargo (Delivered & Returned)				192,851
Residual Propellants				4,024
	Main Propellant Residuals		2,889	
		LOX		
		LH2		
	RCS/OMS Residuals		1,135	
OMS/RCS Reserve Propellants				2,270
Landed Weight				**323,508**
RCS Entry Propellants				1,091
Entry Weight				**324,599**
RCS/OMS Propellants (on-orbit)				21,613
	OMS		18,960	
	RCS		2,653	
Cargo Discharge				0
Ascent Reserve Propellants				2,889
	LOX		2,524	
	LH2		366	
Inflight Losses and Vents				3,246
Insertion Weight				**352,347**
Ascent Propellants				577,849
	LOX		504,704	
	LH2		73,145	
Gross Liftoff Weight				**930,197**
Startup Losses				5,778
	LOX		5,047	
	LH2		731	
Maximum Pre-Launch Weight				**935,975**

Second Stage

				Level 2	Level 1
1.0	Wing Group				1,588
2.0	Tail Group				950
3.0	Body Group				14,146
		Primary Structure		8,776	
		Seondary Sructure		413	
		Crew Cabin		2,272	
		Body Flap		0	
		Thrust Structure		426	
		LOX Tank		865	
		LH2 Tank		1,394	
4.0	Thermal Protection				6,472
5.0	Landing Gear				2,200
6.0	Main Propulsion				3,833
7.0	RCS Propulsion				749
8.0	OMS Propulsion				781
9.0	Primary Power				6,144
10.0	Electrical Conversion & Dist.				3,540
11.0	Hydraulic System				0
12.0	System Control Actuation				321
13.0	Avionics				1,750
14.0	Envronmental Control				4,166
15.0	Personal Equipment				3,015
16.0	Dry Weight Margin				7,448
	Dry Weight				**57,104**
17.0	Crew and Gear				8,256
18.0	Payload Provisions				0
19.0	Cargo (Delivered & Returned)				0
20.0	Residual Propellants				829
		Main Propellant Residuals		595	
			LOX		
			LH2		
		RCS/OMS Residuals		234	
21.0	OMS/RCS Reserve Propellants				468
	Landed Weight				**66,657**
22.0	RCS Entry Propellants				225
	Entry Weight				**66,881**
23.0	RCS/OMS Propellants (on-orbit)				4,453
		OMS		3,907	
		RCS		547	
24.0	Cargo Discharge				0
25.0	Ascent Reserve Propellants				595
		LOX		520	
		LH2		75	
26.0	Inflight Losses and Vents				669
	Insertion Weight				**72,599**
27.0	Ascent Propellants				119,062
		LOX		103,991	
		LH2		15,071	
	Gross Liftoff Weight				**191,661**
28.0	Startup Losses				1,191
		LOX		1,040	
		LH2		151	
	Maximum Pre-Launch Weight				**192,851**

Appendix C: Vehicle Gross/Dry Weight Curve Fits

Sub-orbital

$$GW_1 = -1.971x^2 + 230.5x + 6011.2$$
$$DW_1 = -.79x^2 + 82.9x + 4128.8$$

$$GW_2 = -2.978x^2 + 385.7x + 4169.9$$
$$DW_2 = -2.546x^2 + 239.1x + 3566.2$$

One-Orbit

$$GW_1 = -20.64x^2 + 2408.1x + 41609$$
$$DW_1 = -4.22x^2 + 421.6x + 9522$$
$$GW_2 = -5.2x^2 + 717.8x + 8883$$
$$DW_2 = -2.58x^2 + 275.6x + 4145.8$$

Multi-orbits

$$GW_1 = -34.46x^2 + 4021.53x + 69487$$
$$DW_1 = -7.05x^2 + 704.1x + 15901.7$$
$$GW_2 = -8.68x^2 + 1198.7x + 14834.6$$
$$DW_2 = -4.31x^2 + 460.25x + 6923.5$$

Orbital Docking

$$GW_1 = -41.27x^2 + 4816.2x + 83218$$
$$DW_1 = -8.441x^2 + 843.2x + 19044$$
$$GW_2 = -10.39x^2 + 1435.6x + 17766$$
$$DW_2 = -5.162x^2 + 551.2x + 8291.6$$

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